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ROBOTIC WORK CELL FOR PACKING CANISTERS

by

Robert J. Makar

in

Partial Fulfillment

of the

Requirements for the Degree of

MASTER OF SCIENCE

in

Mechanical Engineering

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ROCHESTER, NEW YORK

DECEMBER 1986

title of Thesis Robot Work Cell For  
Packing Canisters

Robert J. Makar

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## ABSTRACT

The purpose of this project is to reduce the manufacturing cost of the special order 2500cc truck canisters produced at Rochester Products' Lee Road facility. This was accomplished by designing and developing a robotic work cell to pack the canisters into baskets at the injection mold machine. A literature search was conducted to gain a broader understanding of robotic applications and end-effector design. In developing this cell, the layout of the work cell components was determined, a suitable robot was selected, and an end-effector was designed, built and tested.

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## CHAPTER I: INTRODUCTION

Robots have been quickly accepted in the industrial world as highly successful tools for increasing productivity. Since robots are fairly new and important to industry, it was the author's hope to learn more about robots and how to successfully implement them.

Today's markets are changing more rapidly than in the past. Because of these rapid changes, industry has been finding it difficult to economically change over its hard tooled, dedicated manufacturing systems. In many industries it is no longer cost justifiable to build large high volume production equipment to be scrapped in a few years due to market changes. The strongest quality robots have to offer to the world of manufacturing is that they can be retooled and reprogrammed to handle changes in production requirements at a relatively low cost.{1}\*

Another important reason why robots are becoming popular is their ability to work continuously without taking a break, starting late, or calling in sick. Thus they are continuously productive. Robots also have very high repeatability which allow them to produce a very high quality product since it is unlikely they will make a mistake. Hence, the scrap rate is lowered, driving the product cost down. High repeatability also allows for less material waste in operations such as welding and spray painting, because robots can be programmed to accurately repeat a sequence of steps.{2}

Robots relieve workers from less desirable jobs. They can easily handle many dull and monotonous jobs which workers are currently assigned. In dangerous work environments robots are unaffected by toxic chemicals, high temperatures and high levels of contaminants.{3}

Just as robots are suitable for many tasks, there are many manufacturing situations which are better handled by other manufacturing techniques, including hard automation and manual labor.

### Robots vs. Hard Tooled Automation and Manual Labor

The methods by which a product can be manufactured can be divided into three separate categories which are: hard tooled automation, robotic work cells, and manual labor. Hard tooled automation is defined as a system of tools working together in a synchronous fashion. It is also referred as dedicated tooling,

\* - All numbers in brackets {} are reference numbers given on page 70.



that is, tooling which is dedicated to produce one product. The next type, robotic work cells, are ideally set up to produce a particular product until the production run is complete. After the run is complete, the cell is reconfigured to produce a different product. Finally, manual labor is defined as those jobs for which an operator does the majority of the work. For the sake of comparison, we will consider manual labor to handle tasks which are essentially piece-work.

An illustrative way of understanding the effectiveness of each manufacturing technique is to compare the cost of producing a single part as a function of the production run volume. This is shown in Figure 1.(4)

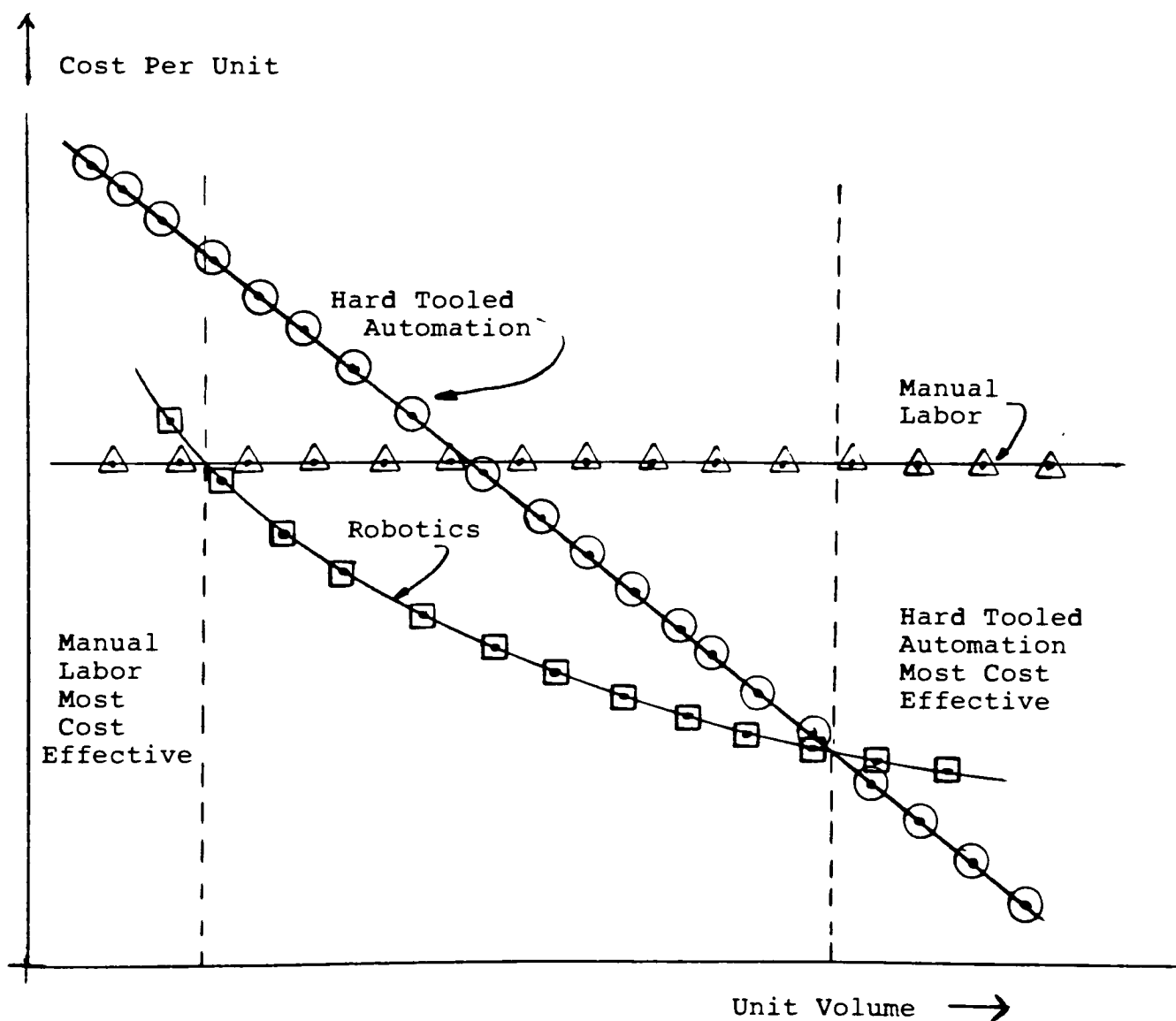


Figure 1: Manufacturing Cost Comparison

This chart illustrates that if a small number of parts are going to be produced, it is most cost effective to use manual labor since minimal capital expenditures are required. On the other hand, if a relatively large number of parts are to be produced, hard tooled automation would be the most cost effective method. Finally, robotics is most cost effective if used in medium volume jobs since a robot's implementation is less costly than automation production line. Thus, less parts have to be produced by a robot work cell in order to earn a pay back.{5}

A robot is well suited for batch processing where a job runs for a predetermined period of time(i.e. 1 shift, 1 week, 3 months). At the end of the batch, the robot can be retooled and reprogrammed to run the next batch of parts. Compared to hard tooled automation, a robot can be changed over very quickly to handle the next production run.{6} A robot is also well suited for applications which require the dexterity that hard tooled automation cannot provide. The work cell environment, however must be very structured to ensure that the "blind" robot will be able to find what it is seeking.{7}

#### Examples of Robot Tasks

Today, robots are performing many tasks throughout industry. Below is a listing of the different areas in which robots are being currently used.

- Welding : Spot, MIG, TIG
- Painting : Spray
- Material Handling : Machine loading/unloading, parts transfer, parts sorting, palletizing, part manipulation during a manufacturing operation
- Tooling : Drilling, cleaning, deburring, material removal operations
- Inspection : Digital vision systems, laser inspection, sorting out rejects
- Assembly : Electronic components, automotive components, consumer appliances

## Basic Types of Robots

Robots are categorized by the type of coordinate system used to describe its arm's end point in free space. The five major types of robots are Cartesian Coordinate, Cylindrical Coordinate, Spherical Coordinate, Fully Articulated, and Scara configuration. Figure 2 shows a diagram of each type of robot. {8}

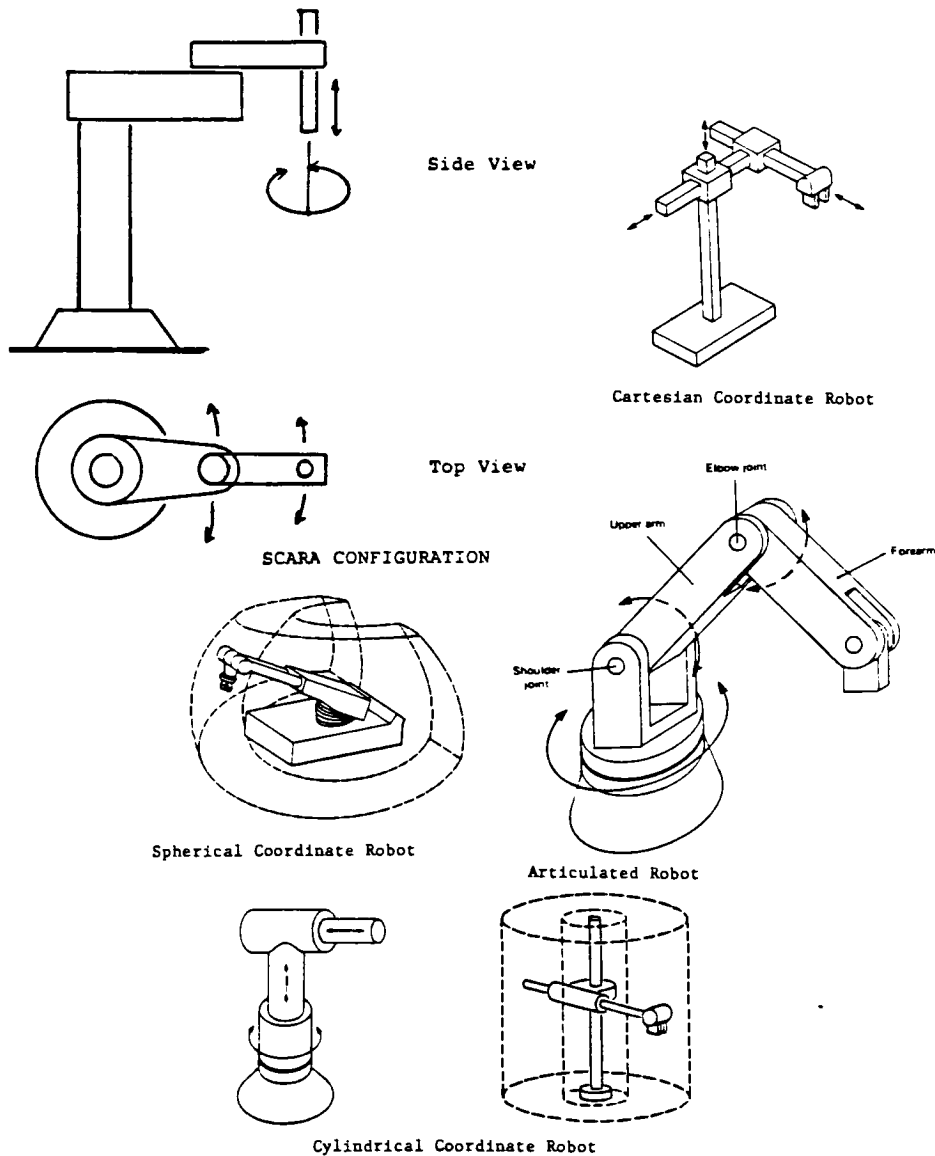


Figure 2: Different Robot Configurations

Below is a table showing the different tasks each type of robot is best suited for.

Table 1: Various Applications for Different Types of Robots

ROBOT	APPLICATION
Cartesian Coord.	<ul style="list-style-type: none"> <li>- Machine Loading</li> <li>- Material Handling</li> </ul>
Cylindrical and Spherical Coord.	<ul style="list-style-type: none"> <li>- Material Handling</li> <li>- Machine Loading</li> <li>- Tooling and Inspection</li> </ul>
Fully Articulated	<ul style="list-style-type: none"> <li>- Spray Painting</li> <li>- Welding</li> <li>- Sealant Application</li> <li>- Deburring</li> <li>- Drilling</li> <li>- Material Handling</li> <li>- Machine Loading</li> <li>- Tooling and Inspection</li> </ul>
SCARA Configuration	<ul style="list-style-type: none"> <li>- Small Parts Handling</li> <li>- Assembly</li> <li>- Electronic Assembly</li> <li>- Small Materials Handling</li> </ul>

The more articulated the robot, the higher the number of tasks it is capable of doing. With this added dexterity, however, comes a higher price. Thus if only a very simple task needs to be done, one may consider using the simplest type of robot available that can do the task.

The three different types of power systems typically used for robots are hydraulic, pneumatic, and electrical systems. The three tables which follow show the advantages and disadvantage of each power system.

Table 2a.: Hydraulics

ADVANTAGES	DISADVANTAGES
-Remote power source	-Complicated positional control and servo feedback system
-High power-to-weight ratio	-Difficult to maintain
-High power to volume ratio	-Power source takes up additional floor space
-Minimal weight on manipulator	-Very sensitive to dirt or foreign particles in the fluid system
-Medium priced systems	-Fluid systems leak and may be unacceptable for many applications

Table 2b.: Pneumatic

ADVANTAGES	DISADVANTAGES
-Remote power source	-Power source requires additional floor space
-Can tolerate a more industrial environment than a hydraulic system	-Poor power-to-weight ratio
-Inexpensive system	-No servo feedback or positional controls
	-Poor power-to-volume ratio

Table 2c.: Electric

ADVANTAGES	DISADVANTAGES
-Very tolerant in an industrial environment	-Power source is on the manipulator thus decreasing effective payload
-Excellent positional and repeatability capabilities	-New technology and current maintenance staff may need time to learn the control sys.
-Good power-to-weight ratio	-Higher cost
-Rapid response time	-Not suitable for explosive environments
-Minimum contamination problems	

Depending on the application, the robot's power system should be considered first. For example, if the robot is to move heavy objects, a hydraulic power system will provide the necessary payload capacity. However, if the robot is to be used in a clean room of an electronics facility, a hydraulic system will not be acceptable due to potential hydraulic fluid leakage; whereas an electrically powered robot will be well suited.

### Controller System

The two most popular methods used to control a robot's motion are the point-to-point method and the continuous path method. A robot which uses the point-to-point method travels from one point in free space to a second point in free space on an arbitrary path. The path taken may not be the shortest but it is usually the quickest. The drives on each of the robot's axes start and stop simultaneously. The joint which requires the longest time to complete the maneuver moves at full speed while the others move at a slower speed so the motion on all the joints finish concurrently.{9}

A robot which uses the continuous path method has a defined motion through free space. The path end points and the path itself must be programmed. The drives on each of the axes, therefore, activate in a coordinated and synchronous fashion. Most continuous path robots are used in applications such as welding and spray painting.{10}

## Programming Methods

The major advantage a robot has over other types of manufacturing equipment is its ability to be reprogrammed. The three methods of programming a robot are the teach pendant method, off-line programming method, and the free-world teach mode method. The teach pendant method is the most common of the three, and almost all early industrial robots were programmed using this method. As robots and controller technology progressed, off-line programming became available. The newest way to program robots is the free-world teach mode.

The teach pendant is a direct communication link to the robot's controller giving the programmer full control over the robot's motion. Using the controls on the teach pendant, the programmer positions the robot as well as he can by eye. Next the programmer depresses a "teach" button signaling the controller that this is a point the robot must reach during normal operation. Once fully programmed, the robot will repeat the sequence until it is reprogrammed. This method has the advantage of the programmer being close to the robot to see the position of the robot relative to the work cell. It is difficult, however, to precisely position the robot. This method is also not all that safe. In addition, production must be interrupted for reprogramming.{11}

The off-line programming method requires the programmer to sit down behind a CRT and to program, in code, the movements of the robot. A sequence of code might be like this :

```
0001 GOTO PT (X1,Y1,Z1)
0002 ROTATE THETA (1.570)
0003 CLOSE (0.1250)
0004 GOTO PT (X1,Y1,Z2).
```

The GOTO command means the end of the manipulator must go to that point in space. The ROTATE THETA command means rotate the wrist along the theta axis 1.570 radians. The CLOSE means the jaw would close 0.1250 inches. And finally, the last GOTO command would mean to go to the second point in space.

The major advantage of off-line programming is that the robot can be programmed away from the factory floor and doesn't interrupt production. Using this method, the routines can be easily edited. Small subroutines can be added and deleted to adjust the whole system slightly to compensate for such things as changes in the product or production, changes in the work environment (i.e.: displaced parts positioners or other external hardware) and changes in operating parameters (i.e.: faster welding speeds). The major disadvantage to this system is the programmer may have difficulty in "seeing" what he is programming. But with the recent developments in multi-color computer graphics, this problem is becoming of lesser concern.{12}

The newest technique in programming is the free-world teach mode programming method. This method needs only a short set-up time and is easy to use. With the robots drive mechanism in neutral, the robot is manually moved to the correct position and a "teach" button is depressed signaling the robot to come to this point at this step in the sequence. The method has the same disadvantage as the teach pendant method since the positional accuracy is dependent upon the programmer. However, the robot can be quickly repositioned and taught a new point. This quickness makes the free-world teach mode very attractive for the development environment when several different manipulation sequences are to be compared.{13}

Several newer robot systems incorporate all three programming methods. This allows the programmer to utilize the advantages of all three techniques.



## CHAPTER II : PROBLEM AND TASK DESCRIPTION

The purpose of this work was to develop and design a robotic work cell to palletize Rochester Product's 2500cc fuel canister after injection molding. In addition to developing the cell, the robot's end effector was designed, built and tested.

A sketch of the canister is shown in Figure 3. The function of the fuel canister is to capture excessive fuel vapors from the fuel tanks on General Motor's trucks. The captured fuel is then routed to the carburetor for combustion. The canister is an injection molded nylon part with a 6.50 in. diameter and is approximately 6.25 in. tall.

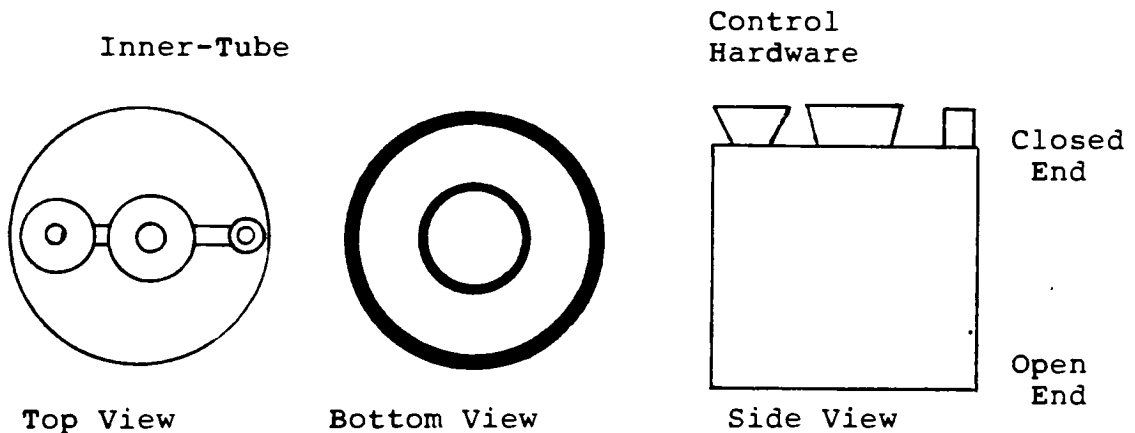


Figure 3: 2500cc Truck Canister

Currently, 3000 canisters are produced daily. The canisters are manufactured in three stages: the injection molding stage, the sub-assembly stage, and the final-assembly stage. The canisters enter and leave each stage on an overhead conveyer system which has two parts buffers between each of the three stages (see Figure 4). The canisters arrive at the parts buffer randomly. Thus, the entire buffer must be cleared before a different canister model can be released to the conveyer system.

The requirement that the buffer be cleared creates a logistics problem when a small lot (500-1000 pieces) must be produced. Normal production lots are in the order of 3000 per day and the time to clear the parts buffer is about 4 hours. The small lots must be produced concurrent with normal production, yet remain physically segregated. To maintain separation of different lots, each small lot of canisters are transported between production stages in large baskets which are manually loaded and unloaded at each of the three stations. This necessitates one person per shift at each of the stations as additional staff just for small lot production. Thus, the objective of this project was to reduce the amount of manual labor required to produce the small lots canisters.

It was proposed to automate the loading of canisters into the basket at the injection molding machine by using a robotic work cell. One work cell was initially planned and after favorable technical and financial evaluation, and/or modifications, the remaining two work cells for the subsequent assembly line would be implemented. The proposed work cell included the injection molding machine, the robot, the basket to be loaded with canisters, and a test stand. The test stand was included to insure 100% inspection of the small lots before they went to the sub-assembly stage. This 100% inspection assured the company of the highest quality canisters which was a particular problem of small lot production.

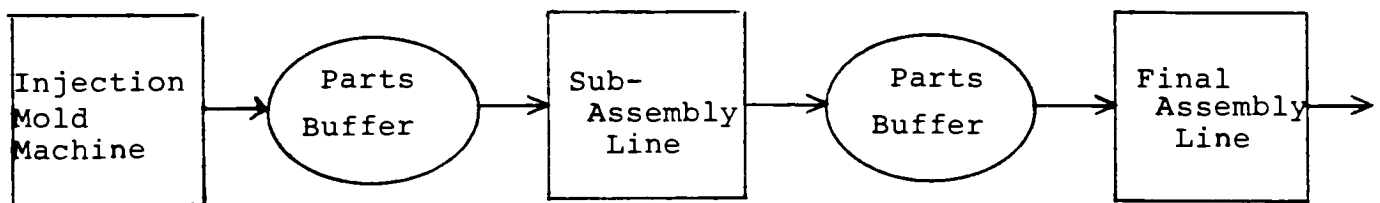


Figure 4: Production Flow Path

### CHAPTER III : SIMILAR APPLICATIONS

#### AND APPLICATION IDEAS

As with most design projects, it is imperative to thoroughly research the subject matter before design begins. Presented here are the findings of a literature search on robotic work cells. The two main categories which were investigated are robotic machine loading/unloading and robotic palletizing operations.

#### Machine Loading/Unloading

Machine loading/unloading is a popular robotics application. Today, many production machines are highly automated and computer-numerically-controlled (CNC). Once set-up, the operator is required only to load the parts on and off of the machine. He is idle while the machine is running, thus poorly utilizing his time. A robot dedicated to loading and unloading the machine allows the operator to set-up a second machine or perform other important tasks.{14} Several layout ideas stem from this concept. One arrangement is to have several machines attended by one robot as shown in Figure 5. This allows for full utilization of the robot. The robot can also do other tasks in addition to loading the machine, such as machining the part further (i.e.: drilling, deburring), inspecting the part, or as with this application, palletizing the part.{15}

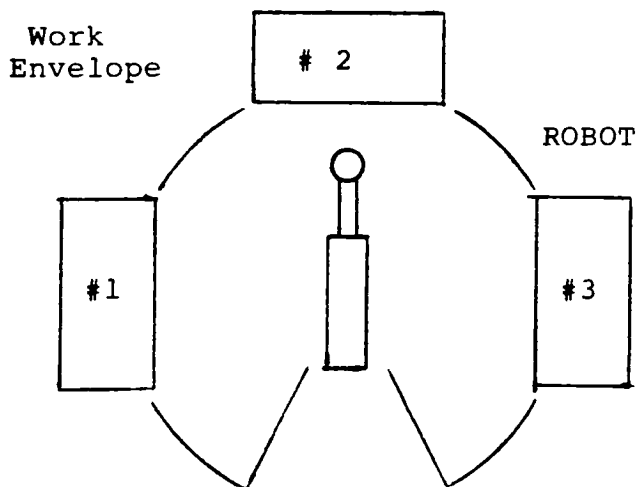


Figure 5: THREE MACHINES SERVICED BY 1 ROBOT

At General Motors , for example, ten punch presses in series are required to bring a sheet metal part to its final shape. As originally set up, each of the ten presses had an operator. The part was manually placed in the press, the unit was activated, the part removed and passed to the next station. This punch press line was reconfigured and now there is a robot at each press station putting the parts into the press, removing them, and then passing it to the next robot as shown in Figure 6. The robots used in this application are the GMF M-1A robot, an electrically powered cylindrical coordinate robot.

The new robotic punch press line produces parts at a slower rate than the manned line, but the daily output of the line has increased. This is because the robots work continuously through all breaks and shift changes, and the reduction of scrap rate due to the robots' high repeatability.

The last robot of the sequence also loads the parts into baskets (these baskets are very similar to the ones which will be used in this project). To allow a better reach capability, the front gate on the basket is folded down. To assist with the loading of the parts, the end-effector has been designed to place cardboard separators between each layer of parts.

To ensure that the production flow is not interrupted, two baskets are made available for the last robot to pack. When the first basket is full, the punch press line continues to run with the last robot now packing the second basket. The full baskets are removed by the set-up man and replaced with empty ones.{16}

When using a robot in a machine tending application, as in the above example, cycle time must be considered. The cycle time of the robot and the machine(s) should be fairly well matched. A major factor affecting a robot's speed (cycle time) is the accuracy which the robot must achieve.{17}

Accurate positioning of a part by a robot requires a significant amount of time since the robot needs to slow down and approach that point in very small steps. This is because the controller needs more time to compute the position of the manipulator. The use of a secondary positioning device would eliminate the need for the robot to accurately position the part itself. The robot would drop off the part and the secondary device would position the part. A secondary device adds to the cost of the work cell and needs to be considered to ensure that the work cell remains cost justifiable.

Also, when using a robot in a machine tending operation, area allotment needs to be considered. It is important to minimize the amount of area which the robotic work cell will occupy since factory floor space is limited and very expensive. On the other hand squeezing the work cell tightly together makes it difficult for the maintenance personnel to access the machines

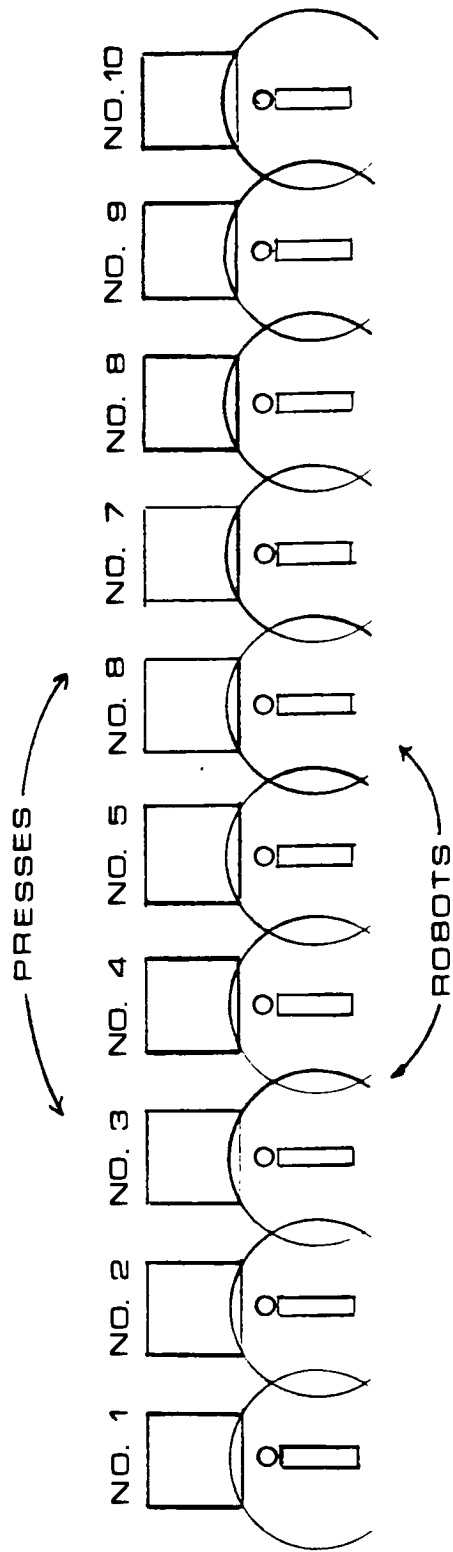


Figure 6: GM's Press Operations

or the robot. It is also advisable to leave enough room in the cell for an operator to take over the operation if the robot breaks down. This is particularly important in a manufacturing system where continuous work flow is essential.{18}

The General Motors' robotic punch press line is an application where the work cell has been arranged to allow operators to easily take over the robot's task. All of the robots are mounted on wheels so that in the event that one fails, it can be removed from the line and an operator can step in to take over the operation. This prevents all ten punch presses and the remaining robots from becoming idle.{19}

### Palletizing

"Automated material handling systems are the backbone of future automation in the factory."{20} An automated factory needs a well ordered environment where materials are accurately located and oriented thus minimizing the amount of material handling in the production process. Good positional and orientative accuracies help "blind" tools, such as robots, to always find the part. An orderly environment also ensures quicker material flow since the parts do not have to be manipulated. Palletizing systems offer an excellent means of achieving this orderly environment.{21}

Several items which should be considered before introducing a pallet or palletizing system into a robotics work cell are system duplication, the use of separator trays, and cycle time.

If a robotic palletizing system is currently in place at the designer's facility, it should be duplicated if that system is working satisfactorily. This duplication has the benefits of having the technical expertise and spare parts already in place. This will make the new implementation more efficient and less costly.{22}

Specialized separator trays are being widely used throughout industry. The use of specialized separator trays has several advantages. They increase the parts' three-dimensional positional accuracy and maintain their orientation during transportation. The trays also help to minimize part damage and present an effective means for inventory control. Some of the draw backs of using trays are that they need to be stored and inspected prior to use, and the propagation of inaccuracies as the trays are stacked upon one another.{23}

In most cases, the given production rate is invariable which determines how many parts the robot must handle at once. If the robot is slow compared to the production rate, it will have to handle two or more parts simultaneously. This leads to new problems such as how to handle multiple parts and how they are to

be palletized. On the other hand, if the robot is much faster than the production rate, the robot may be able to handle an additional task while waiting on the primary task.

An important task a robot may handle if it has the time is the placement of the separator trays. Once a separator tray is full, the robot retrieves another tray and puts it in place. This simplifies the work cell since it will not be necessary to have a secondary device to handle the trays. The robot will also be better utilized. To help facilitate the placement of the trays by the robot, a parts buffer may be used allowing the parts to accumulate while the robot is putting the empty tray in place. Once the tray is in position, the robot will start loading the parts at a faster pace until the buffer is empty.{24}

### Robots Applicable For Palletizing Operation

Certain types of robots work well for palletizing and some do not. Those which are well suited for this application are the articulated robot, the gantry style robot, the spherical coordinate robot and cylindrical coordinate robots. The tables below compare the strengths and weaknesses of these robots for this application.{25} (Also noted in the tables are advantages and disadvantages for loading parts into a basket since that is the objective of this work.)

TABLE 3a.: Articulated and Spherical Robot

ADVANTAGES	DISADVANTAGES
<ul style="list-style-type: none"> <li>-Used effectively in the auto industry for similar applications</li> <li>-High dexterity allowing the robot to maneuver in tight areas</li> </ul>	<ul style="list-style-type: none"> <li>-Horizontal reach capability diminishes at the upper and lower ends of the work envelope</li> <li>-Might be difficult to fully utilize the work envelope. Tipping of the basket may help</li> </ul>

Table 3b.: Gantry Style

ADVANTAGES	DISADVANTAGES
<ul style="list-style-type: none"> <li>-Very effective utilization of the work envelope</li> <li>-Easily covers the pallet area and reaches into the basket</li> <li>-Good floor space utilization allowing trays and baskets to be interchanged</li> </ul>	<ul style="list-style-type: none"> <li>-Problems may occur with the robots inability to obtain parts which are very low to the ground</li> </ul>

TABLE 3c.: Cylindrical Coordinate Robot

ADVANTAGES	DISADVANTAGES
<ul style="list-style-type: none"> <li>-Well suited for a palletizing operation</li> <li>-Horizontal reach remains constant through out the vertical travel of the robot</li> <li>-Better cycle time then the articulated robot</li> </ul>	<ul style="list-style-type: none"> <li>-Requires room behind the robot for the boom to travel</li> <li>-Special end-effector required to "reach" into basket</li> </ul>



## CHAPTER IV : ROBOTIC WORK CELL

### DESIGN CONSIDERATIONS

The objective of this section is to point out several considerations which are important in the development of a robotic work cell. The topics that are discussed are preliminary survey, floor plan layout and safety.

#### Preliminary Survey of Application

The best way to implement a robotic work cell is to survey the task and develop a flow chart for all the steps involved. This helps the designer to clearly understand the entire task. The flow chart should include all actions which will be performed (i.e.: grasp, move, rotate, home), all feedback signals (i.e.: begin cycle, discontinue cycle, emergency stop, end-effector sensory feedback), and all utility steps (i.e.: home, signal output due to system failure, statistics outputs). After the flow chart has been developed and reviewed, the time for each step should be accurately determined. This will reveal any cycle time problems early in the development stage.{26}

Next, the flexibility of the robotic work cell needs to be considered. The work cell may have to accommodate changes in the product which could be tolerance differences or designed changes in the part. The work cell may also need to accommodate changes in the production rate. And for future use, the system may have to communicate with other equipment which will ease the way for a fully automated factory.{27}

The next point of consideration is to determine what type of robot is most feasible for the particular application. To do this, an in-house audit should be conducted of the plant personnel to understand what robot will work best in the designer's facility. For example, if the maintenance personnel are unfamiliar with complicated hydraulic system but are familiar with servomotors, it would be best to use an electrically powered robot over a hydraulically powered robot.{28}

One of the last things which should be considered is the intensity of communication required by the work cell. By examining a well developed system flow chart for the work cell, it is easy to determine the amount of information which needs to be communicated. Many industrial robots offer supplementary packages which allow the user greater interface capabilities, but one should be thoroughly sure that these packages will actually work.

## Floor Plan Layout Considerations

In the floor plan layout development, only the major components need to be considered. This would include: the robot; the controller; the power system if required; and in this case, the injection mold machine, the test stand, the baskets and the reject bin. Even though the floor plan layout is done in a planar fashion, one should not forget about the vertical dimension. With many robots, the maximum horizontal reach changes with the vertical location of the robot's arm as shown in Figure 7.{29}

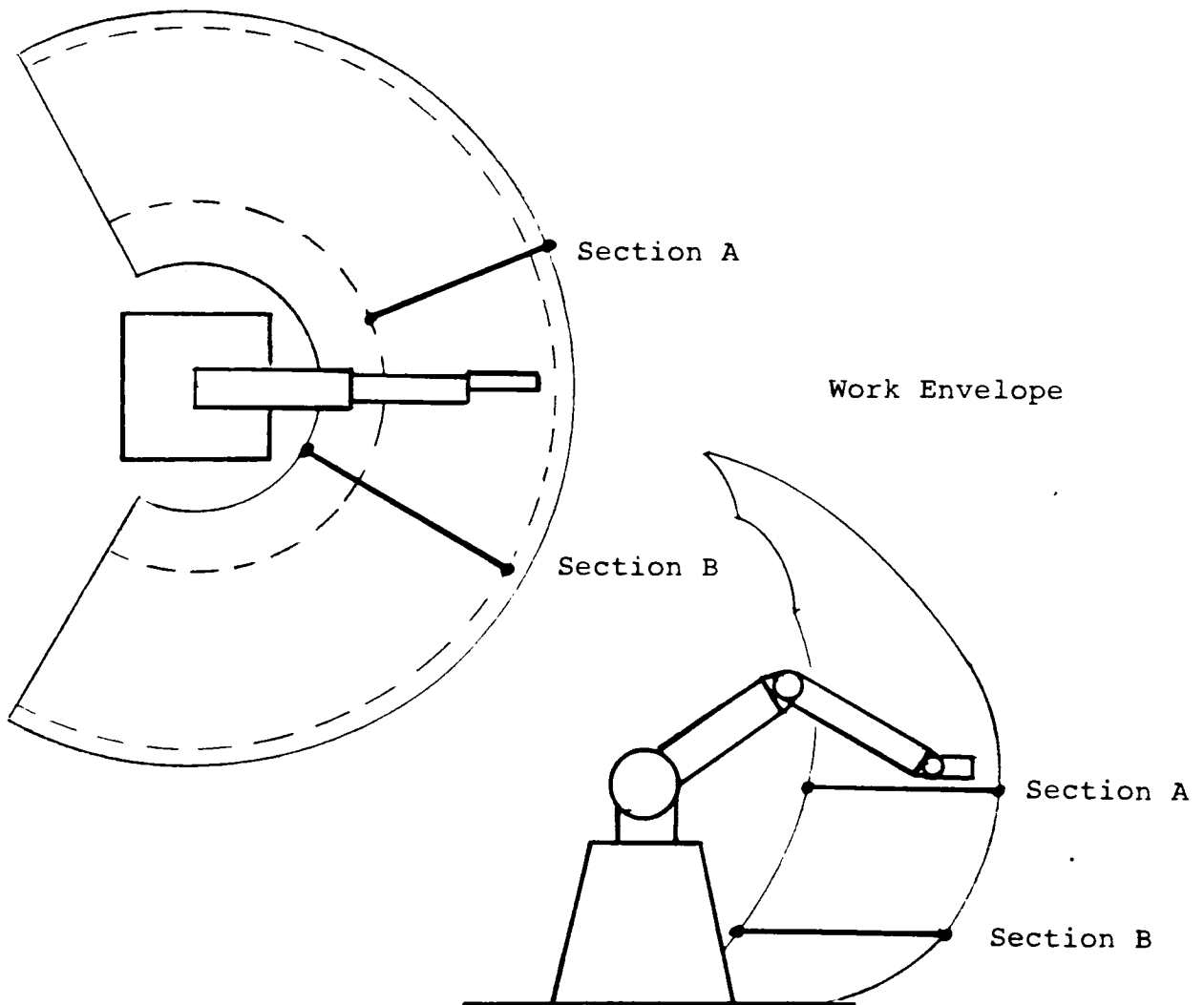


Figure 7: HORIZONTAL REACH AS  
A FUNCTION OF HEIGHT

The robot's controller and power supply unit must also be included in the initial floor plan layout. It is very important to include these two pieces of equipment in the initial layout since floor space is limited and is often difficult to rearrange once it has been allocated.{30}

The best configuration for a robotic work cell is to arrange all of the machines and other equipment so that they are in a circular pattern around the robot as shown in Figure 5. This layout simplifies the application since the robot will not have to yaw (the rotation about the vertical axis at the robot's wrist) to access any of the machines. Adequate clearance should be allowed so maintenance personnel can easily work on the equipment. One clever way to get the necessary clearance is to mount the robot on a track so it can slide in and out of the area. This offers two advantages, it opens up the work area for maintenance and it allows room for an operator to take over the robot's job should it break down. If one elects to use this idea, provisions should be made to accurately reposition the robot in the work space to ensure it does not have to be reprogrammed.{31}

If the work area can tolerate it, position the machines and secondary devices well within the robot's work envelope. This ensures the robot will have adequate reach to compensate for any new changes which may occur.{32}

Many times the opposite of the above case is true. The robot's reach will be inadequate. If this is so, it can be compensated for by implementing an extended reach end-effector. Also, a more elaborate end-effector can be used to add the needed dexterity to a less articulated robot. Thus when planning a layout, the designer should not feel that he is restricted solely to what a particular robot has to offer. With a little imagination, the designer will be able to generate a variety of floor plan layout options.{33}

## SAFETY

Since robots are fairly new industrial tools, and they are closely watched, it is very important that serious considerations are given to safety. The hardest aspect to appreciate about robots is that they are dynamic and capable of moving inadvertently in free space, thus making them exceptionally dangerous. Another aspect of robot safety is that they draw a lot of attention. This leads to problems when spectators become a little too curious and get too close. Thus, extra effort must be given to the safety features of the system. The major safety problems are electrical shock, impact and trapping. Since many standard guide lines for electrical safety are in practice, this hazard won't be discussed here.

The danger of impact and trapping (i.e. pinning an operator against a post) is fairly new safety hazard and deserves some comments. Unexpected movements can occur for the following reasons : software failure, data transmission failure, mechanical failure and electrical failure. Since it is impossible to predict when these failures will occur, the only way to ensure safety is to keep people out of the robot's work envelope while it is running. This is most effectively accomplished by simply building a fence around the robot. This however, may not always be possible. A light curtain or safety mat can be incorporated into the system to shut it down in the event of an intrusion.{34}

Sometimes it is necessary to have someone in the work area while the robot is running. This could be maintenance personnel or the robot programmer. In this event, mechanical stops might be used to restrain the robot in the event a system failure occurs. A clever idea is to "hand-cuff" the robot. That is, to have the end of the robot mechanically attached to a limit switch which would power down the system if the robot "breaks the hand-cuff".{35}

To protect people from the robot and maybe to protect the robot from the people, the designer has many options when considering the safety aspect of the robot. Safety is important for a successful robotic implementation for two reasons. First and foremost, no one should be exposed to a hazardous environment. Second, it will be more difficult to implement future robotic applications if current applications have a poor safety record.

## CHAPTER V: PROPOSED ROBOTIC WORKCELL

This chapter is divided into two sections. The first section discusses the components incorporated in the work cell and the cycle time. The second part of this chapter will discuss the robot selection process.

### Chapter V.a : Components

#### Floor Plan Layout

Figure 8 shows the layout area available for the robot installation. Included in this sketch are the support columns which need to be worked around and the aisle which must not be obstructed. In the completed work cell, each injection mold machine will have one robot. In this project, however, only one robot application was considered. Some of the major considerations for the floor plan development were: the injection mold machines and the robots had to be accessible, the baskets had to be cleared quickly and easily, and the overlap of the two robot's work envelope had to be minimized to avoid collision.

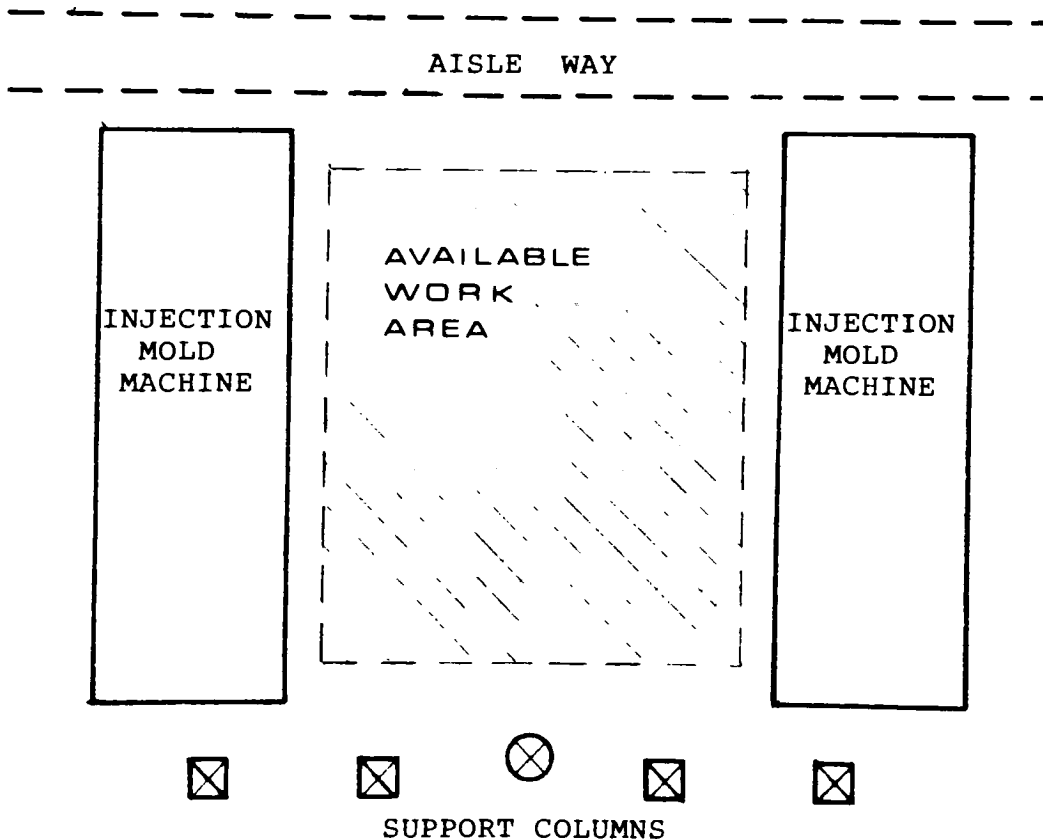


Figure 8: AVAILABLE WORK AREA  
(see Figure B-1, B-3 & B-5 for Dimensions)

## Basket Overview

The basket used in this project is GM's standard basket, the 5531 (Figure 9). It is up to the operator to ensure that the basket used is not bent or distorted. The front upper half of the basket is hinged allowing greater accessibility into the basket. To simplify the robotic loading operation, the front of the basket would always be down, allowing extra room for the robot to "reach" into the basket.

It was decided that the canister would be loaded open end up (see Figure 3). The reason for loading the canister in this position was that the canister comes out of the injection molding machine open end up. In addition, if the end-effector attempted to grasp the canister by the components on the closed end, the components will distort causing the canister to be rejected at the sub-assembly line.

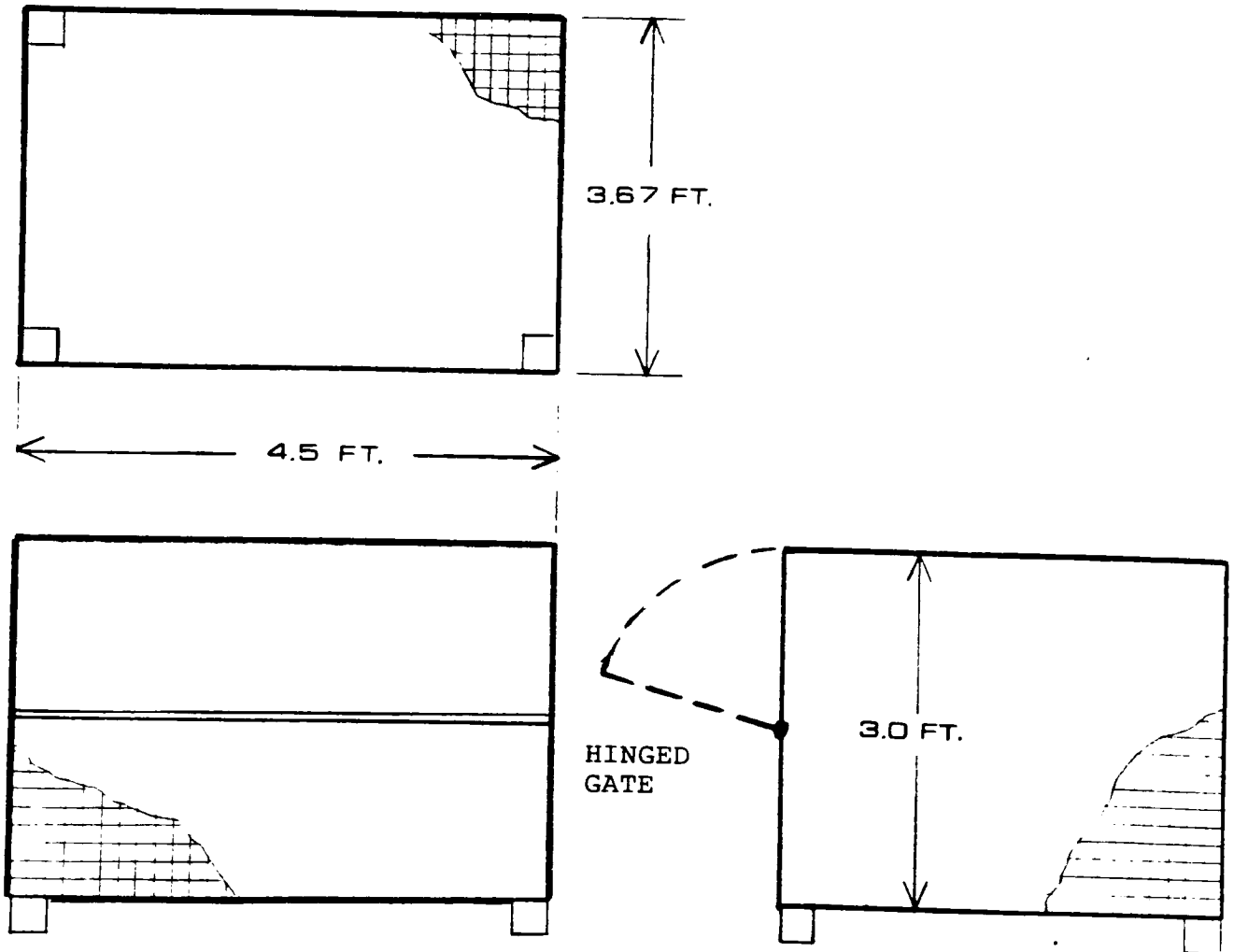


Figure 9: BASKET DIMENSIONS

## Packing Arrangement

The first item considered was the number of canisters which could be loaded in one layer. The canisters were to be loaded in a matrix fashion. The maximum number of rows and columns in the matrix was determined by dividing the canister's diameter into either the width or the depth of the basket. The resulting value was then truncated to give the the maximum number of canisters that would fit in either direction. Next, the clearance between each canister was considered. It was determined that additional clearance would be needed to avoid collisions. In addition, there must be an even number of canisters in the row running parallel to the hinged side of the basket since the canisters must be loaded in pairs (see the Cycle Time section for explanation of loading in pairs). The rows perpendicular to the the side with the gate could have been either even or odd. Figure 10 shows the proposed configuration.

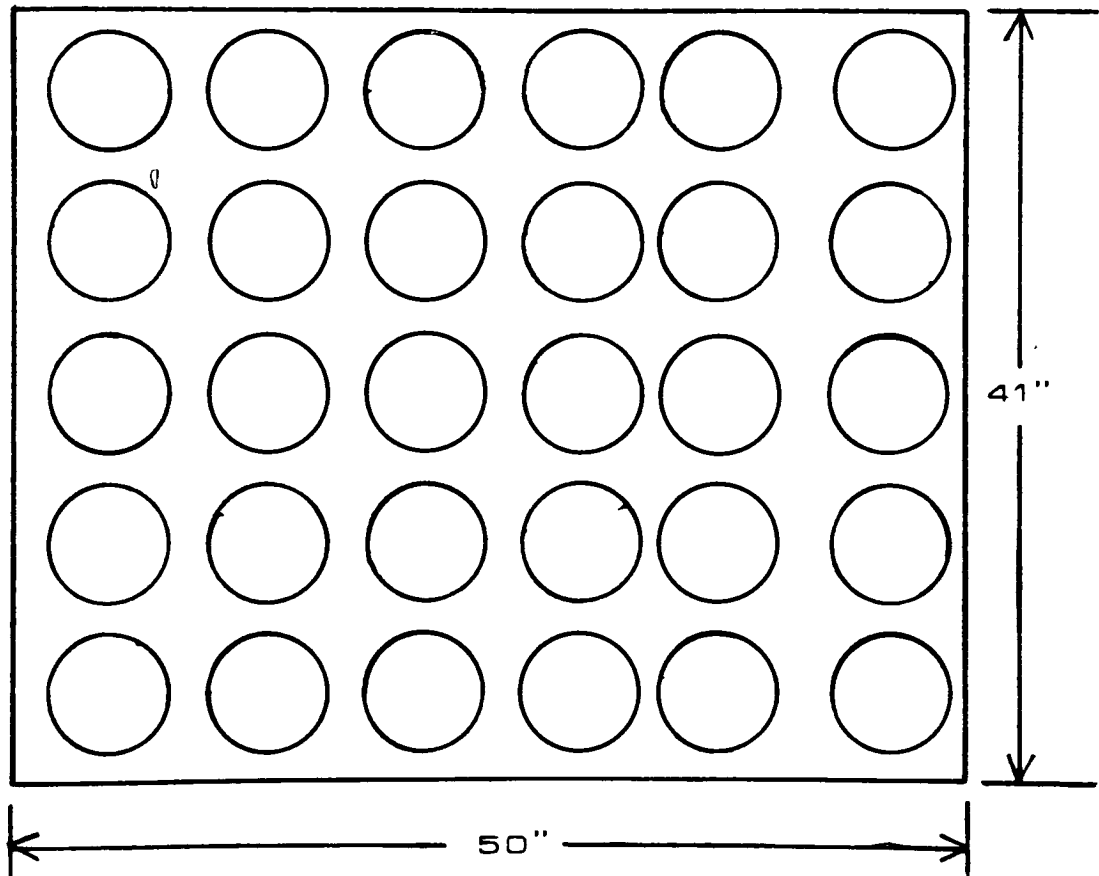


Figure 10: CANISTER ARRANGEMENT IN BASKET

Considering the height available in the basket, the height of the canister and the separator tray thickness, it was determined that four (4) layers could be packed in one basket. This was based on the following assumptions:

- A 1-inch thick separator tray was under each layer of canisters plus a tray on top of the basket.
- The top tray can't be above the top of the basket.

### Cycle Time

In analyzing the cycle time for this application, the following items were considered: the injection molding machine's production rate, the robot's speed to perform various tasks, the support operator's response time, and the test stand's cycle time. The injection mold machine produced parts at a fixed rate of one every 45 seconds.

The major task the robot had to perform was packing the canisters. As a rule of thumb, a robot takes approximately 10 - 15 seconds to pick up a part and place it in a different location. For this application, the robot not only packed the canisters, it also placed the separator trays into the basket.

After discussing the task of placing the separator trays into the basket with the robot manufacturer's application engineers and current robot users at Rochester Products, it was determined that it would take approximately 25 - 35 seconds for the robot to complete this task. Beyond this, once the basket was full, the support operator had to exchange it with an empty one. Opinions on how long this would take varied greatly. (Part of the support operator's daily task would be dedicated to this work cell. His task would include monitoring the machine and exchanging the baskets.)

It is difficult to determine the basket exchange time since it is operator dependent. If the operator is waiting with an empty basket, the basket exchange time can be as little as 15 seconds. If, however, the operator is signaled once the last canister had been packed and then he starts to search for an empty basket, the exchange can take anywhere from 2 - 10 minutes. Therefore, an external signaling device was incorporated to alert the operator that the basket is nearly full. Two baskets could not be used because the robot's work envelope was too small. A parts buffer would be included at the injection mold machine to allow the parts to accumulate when the baskets are being exchanged.

To assist the robot in rapidly clearing the parts buffer, the support operator would place the bottom separator tray in. This eliminated the need for the robot to retrieve a separator tray and place it into the basket, saving 25 - 35 seconds during this step.



The next item to consider was the test stand. It was assumed that the test cycle would take longer than 45 seconds (the injection mold machine's cycle time). The decision was made to test two canisters simultaneously since every canister needed to be tested and the injection molding machine's cycle time could not be altered. This avoided bottle necking at the test stand. To facilitate simultaneous testing, the end-effector would be designed to handle two canisters simultaneously. This allowed adequate time for the robot and the test stand to perform all of the necessary functions.

### Controller Overview

In this section, a brief discussion of the necessary controller hardware is presented. The actual hardware and the programming of the hardware is beyond the scope of this project. The purpose of this discussion is to set down a generic ground work from which the process flow chart can be derived. The major components in the controller system were the supervisory controller, the robot's controller and the injection mold machine's controller. The robot's controller and the mold machine's controller were electronically linked to the supervisory controller. Through these links, the supervisory controller monitored and controlled the cell. Thus the main purpose of the supervisory controller was to act as an interface and overseer of both the injection mold machine and the robot (Figure 11).

The supervisory controller had several other functions. The most important of which was to act as a programmable controller for the test stand. The supervisory controller would keep track

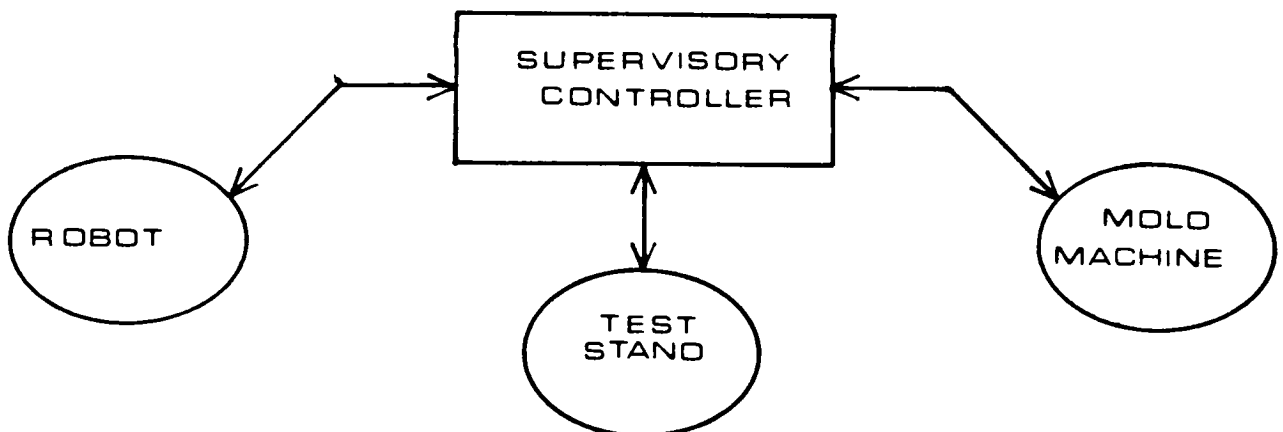


Figure 11: CONTROLLER SCHEMATIC

of the number of rejected canisters, and shut down production while signalling the operator if the rejection count was excessive. The supervisory controller would also signal the operator to prepare for the basket exchange when the one being packed was nearly full.

The programmable controller for the injection mold machine was used to control all of the functions of the machine and to interface with the supervisory controller. The only information to be exchanged between the supervisory controller and the injection mold machine would be a shut down signal when the reject level was exceeded. The supervisory controller would be informed by a set of sensors on the canister handling device when two canisters are ready to be picked up.

The controller for the robot, however, would frequently interface with the supervisory controller. The information to be communicated is:

- Supervisory controller signals robot when two canisters are ready for pick up
- Robot signals supervisory controller when the canisters are in test stand
- Supervisory controller signals robot of test completion and test results
- Supervisory controller tells robot which gripper on dual end-effector is available to pick up canister at the holding stand. (See section on Individual Components, pp 34.)
- Robot checks with supervisory controller to determine if holding stand is open

The robot's controller would be programmed to palletize the canister. The program would also keep count on the number of canisters palletized so that the robot would know when to retrieve the separator trays.

### Flow Chart

Discussed here are the steps which the work cell would go through during all cycles. An explanation is given on the packing and testing routines, and is followed by a description of the routines for placing the separator trays and basket exchanges. A process flow chart (Figure 13) is provided to help the reader understand each of the routines. The most logical place to begin the discussion is as far up stream as possible at the injection mold machine.

After a canister has been molded, the conveyer system brings it to the canister handling device which positions and orients it. Shortly thereafter, a second canister will follow suit and trip a sensor which signals the supervisory controller that two canisters are in place. The supervisory controller then alerts the robot to pick up the canisters.

Once the canisters are grasped, the robot places them on the test stand. Sensors on the test stand then signal the supervisory controller that the canisters are in place and to begin testing.

Once the test is complete, the supervisory controller signals the robot to pick up the canisters and indicate which, if any, canisters failed. The supervisory controller records the defect information (how many and what type, Figure 14).

If both canisters passed, the robot packs both canisters. If one failed and the other passed, the robot will dispose of the rejected canister and hold onto the good canister.

After disposing of the rejected canister, the robot either places the good canister onto the holding stand or picks up a canister which is already there. The supervisory controller keeps track of the status of the holding stand. The holding stand was included in this system to ensure that the canisters are packed in pairs. Trouble arises if the robot packs only one canister with an end-effector designed to handle the canisters in pairs as shown in Figure 12. Packing the canister in pairs greatly simplifies the packing algorithms.

Once a layer is full, the robot needs to retrieve a separator tray. Since both the robot and the supervisory controller are keeping count of the number of canisters actually packed, the supervisory controller knows when the top layer of the basket is nearly full. At this time, the supervisory controller signals the operator to be ready with an empty basket for the exchange.

Since the above process is quite long, a flow chart is provided to show how the routines interact. The flow chart is presented in a generic form so that it be adaptable to any manufacturer's robot controller system(Figure 13).

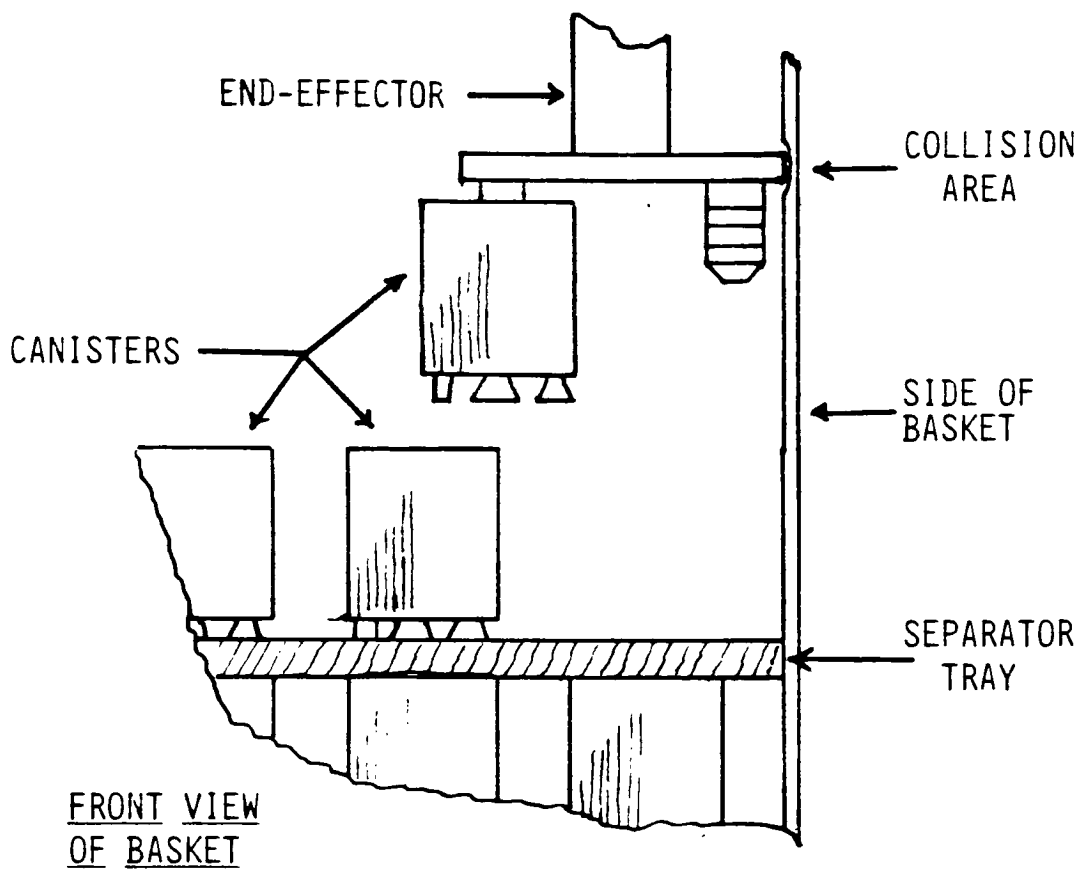
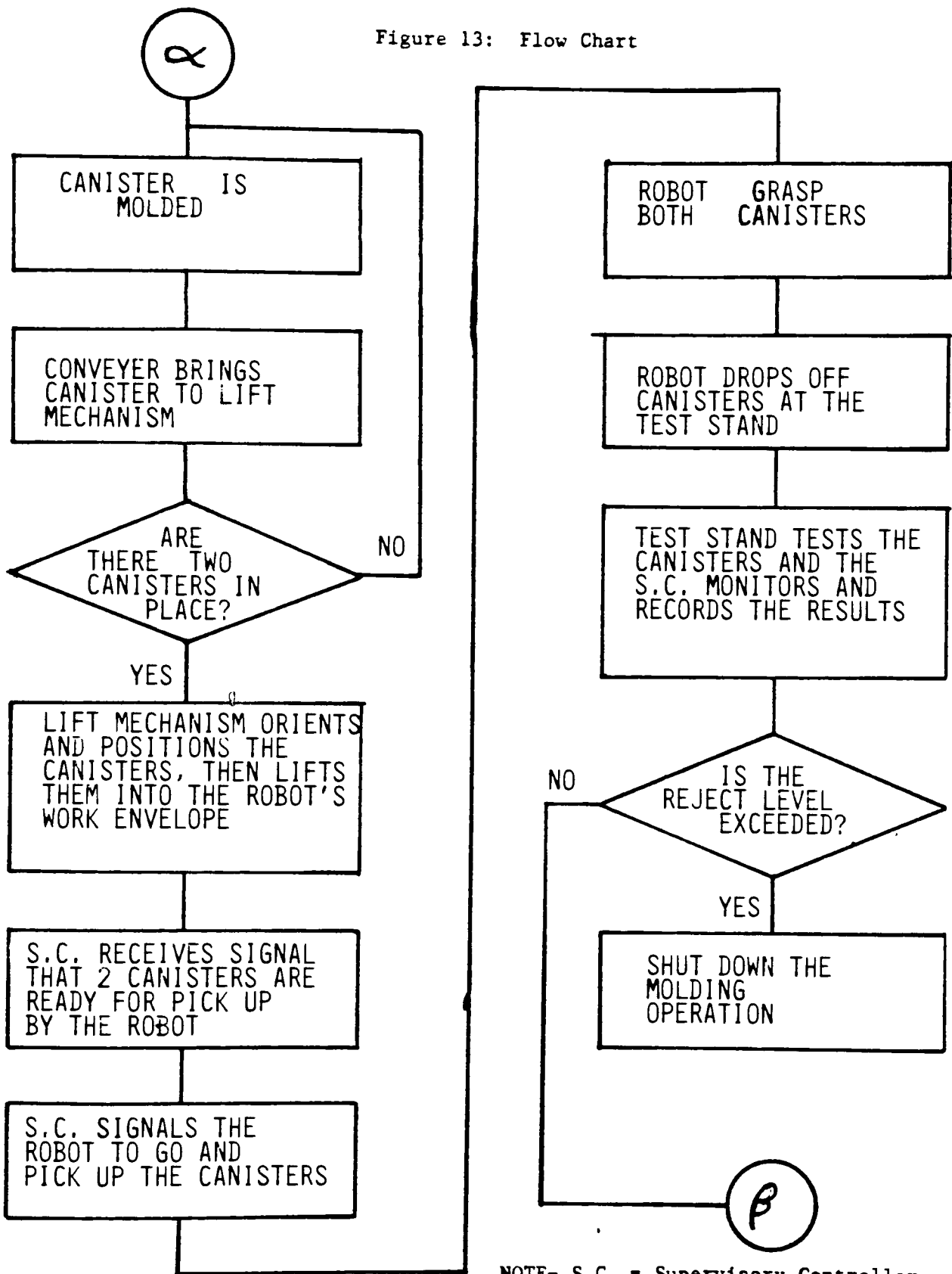


Figure 12: Problem of Packing  
Canisters Singly

Figure 13: Flow Chart



NOTE- S.C. = Supervisory Controller

Figure 13 (cont.)

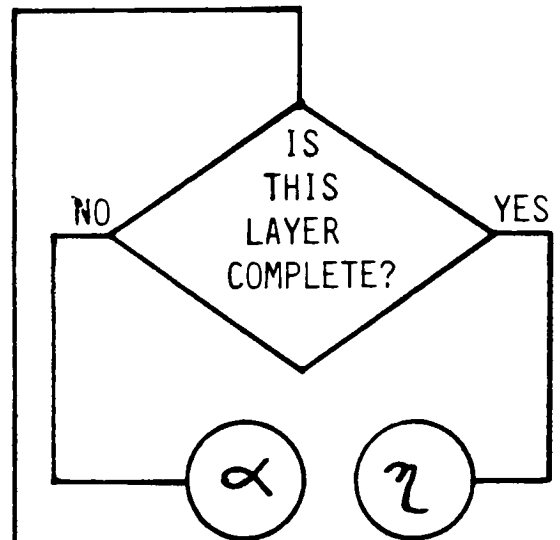
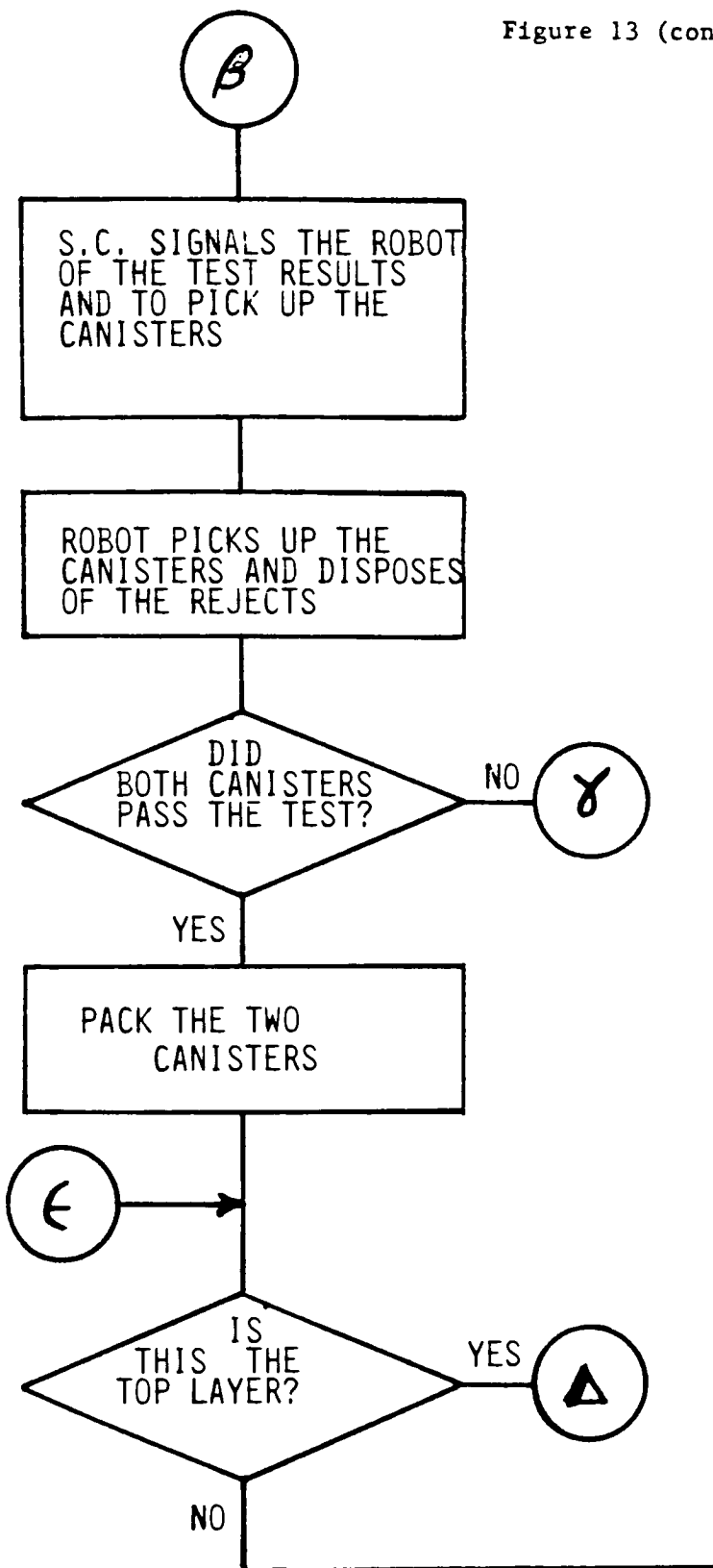


Figure 13 (cont.)

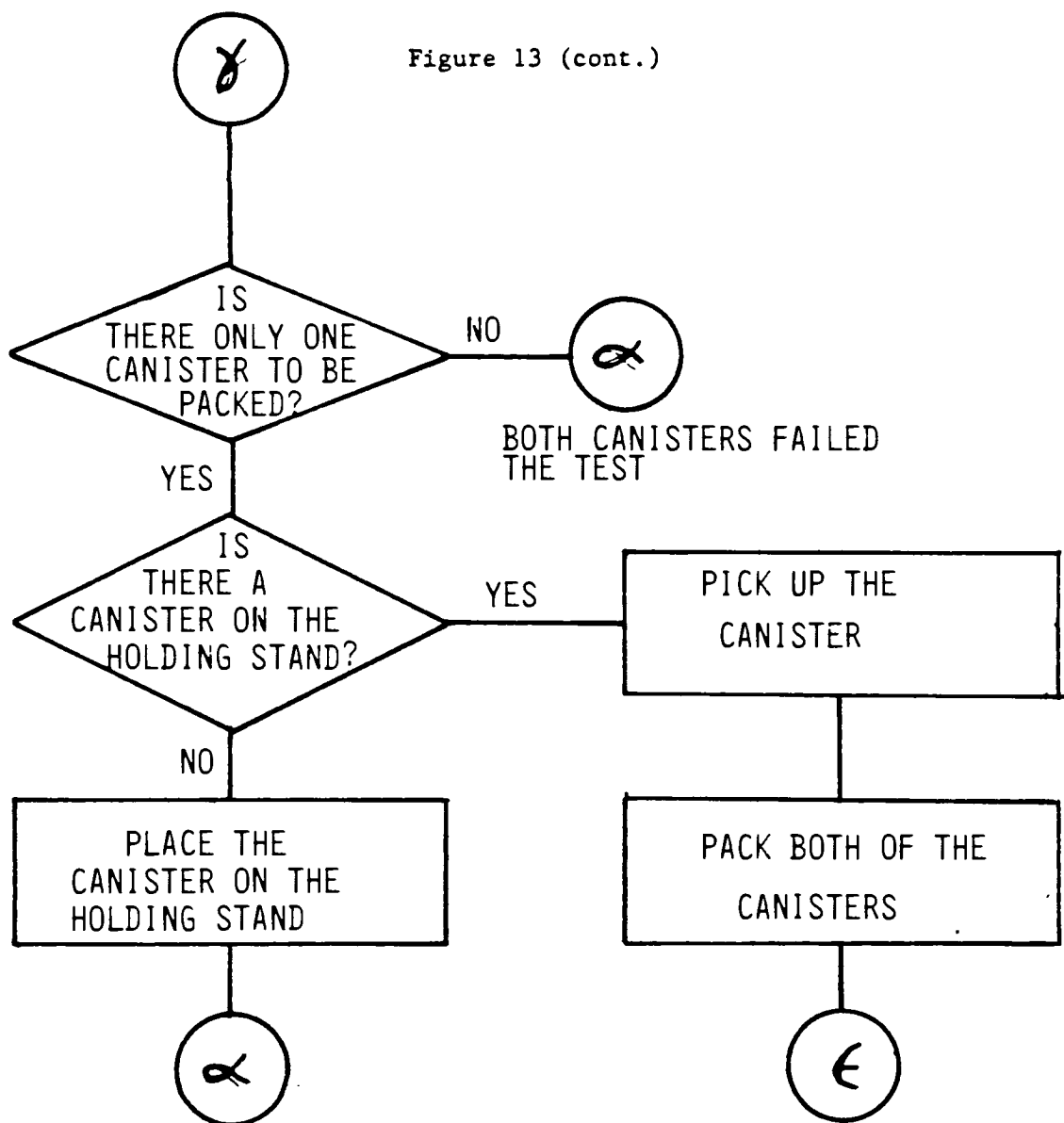
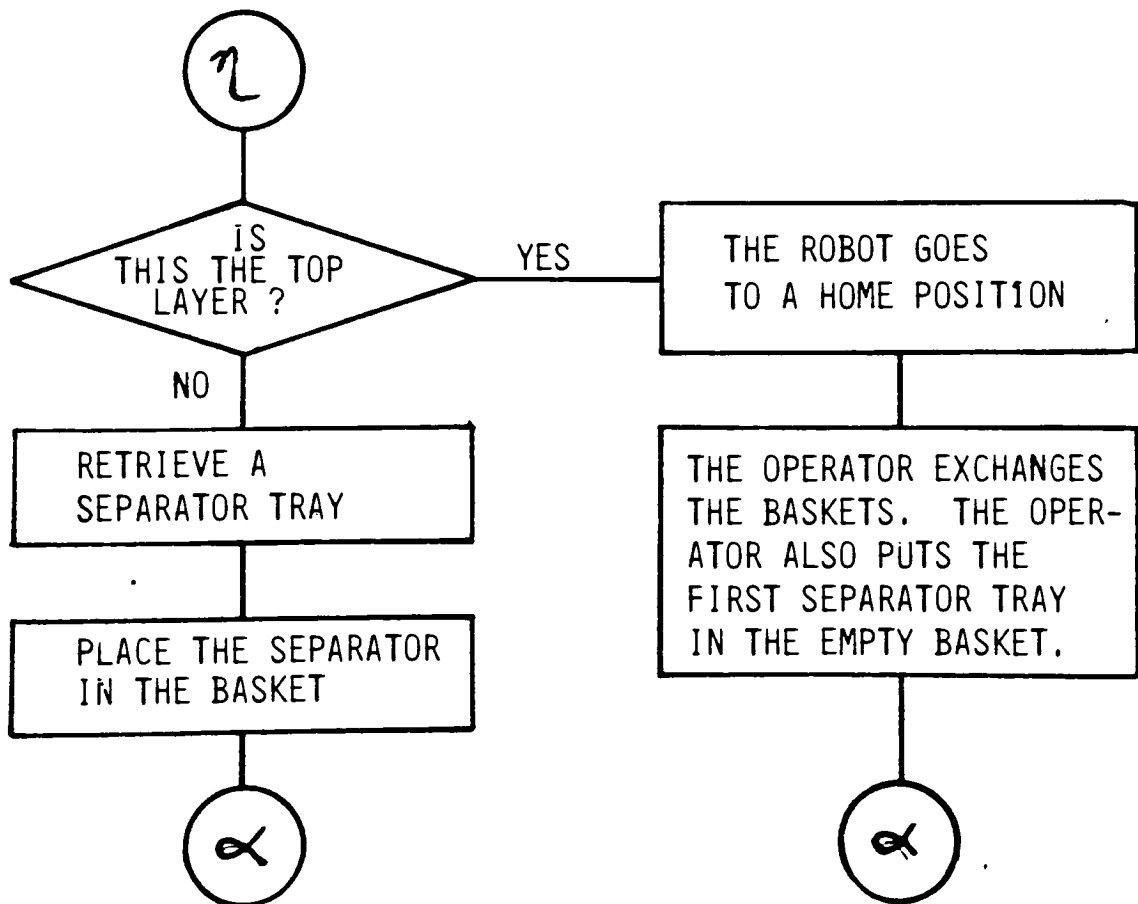
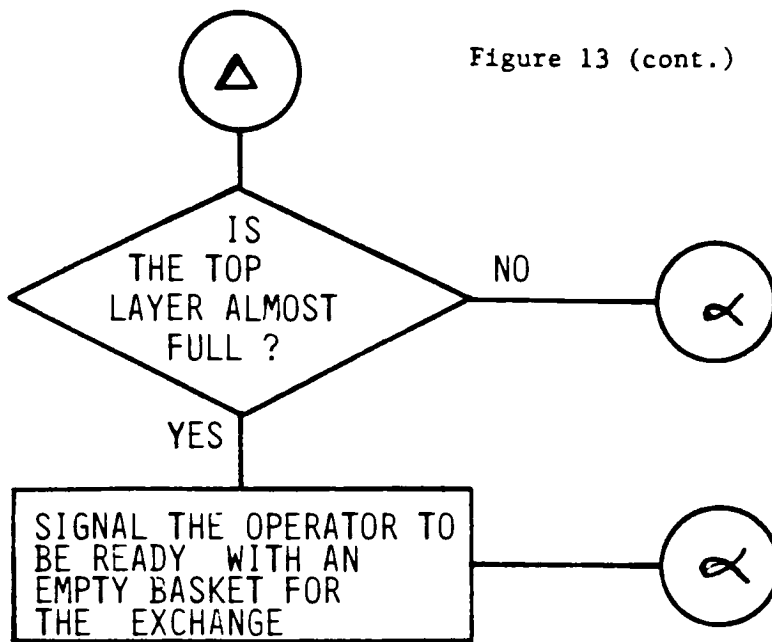


Figure 13 (cont.)





## Individual Components Description

To finalize this part of Chapter V, a description of each major component in the system is given, excluding those already mentioned. The discussion here includes the canister handling device, the test stand, the rejection bin, the holding stand, the basket lifter and the separator trays.

The canister handling device has two components, the canister conveyor and the lifting mechanism. The canister conveyor brings the canister away from the mold to the lift mechanism. The lifting mechanism positions and orients the canisters, and then lifts them into the robot's work envelope. Sensors detect when two canisters are in the lift mechanism and correctly arranged. A parts buffer is located ahead of the lifting mechanism so that the canisters can accumulate on the canister conveyor. This parts buffer was needed to allow the canister to accumulate while the baskets are being exchanged.

The test stand tests all of the canisters for two defects, short shot and hole concentricity (Figure 14). Short shot is the incomplete flow of plastic into the cavity. Hole concentricity refers to concentricity of the valve stem hole relative to the seal area on the center component on top of the canister. This hole must be concentric in order for the canister to operate correctly. Several methods exist for testing for each of these defects. The test methodology is beyond the scope of this paper.

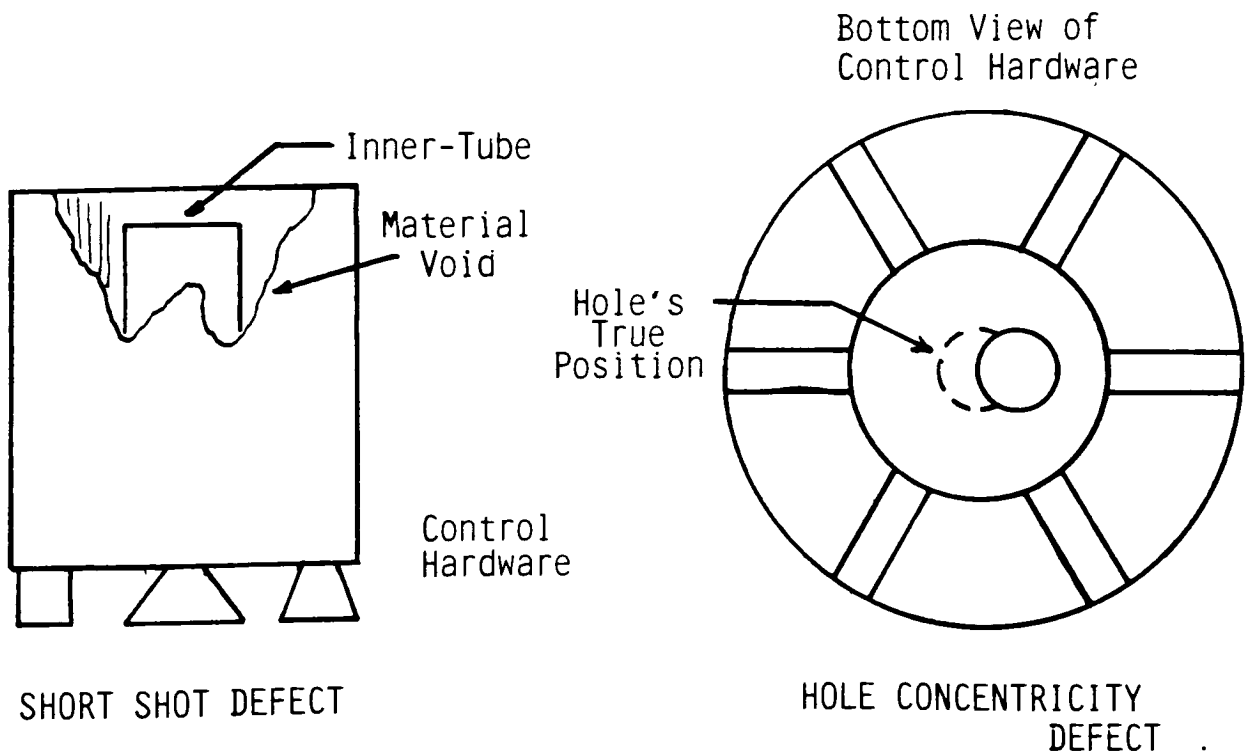


Figure 14: Common Injection Molding Defects

The basket for holding the rejected canisters is similar to the basket used for good parts. If the injection mold machine operated correctly, this bin easily holds a full day of rejected canisters. To ensure the bin is in the correct position, mechanical stops are mounted to the floor.

The holding stand is a nest configured to accurately hold the canister. A limit switch mounted on the stand signals the supervisory controller that a canister was in place.

If the basket were placed on the floor, the robot would not be able to reach the bottom. Thus, a lifting mechanism is required to bring the basket up into the work envelope. The lifting mechanism must accurately position the basket to ensure good repeatability and successful loading of the canisters.

## Chapter V.b : ROBOT SELECTION

The final system design and the design of the end-effector depend directly on the robot selected. The gantry style could not be used because the injection mold machine needs significant clearance to allow the molds to be exchanged. The Scara robot's work envelope and the payload capacity was too small for this task.

The selection of a robot is based on the robot's speed, work envelope size and profile, articulation, controller capability, and price. All of these characteristics must be considered simultaneously to understand the trade offs. Here, the decision process was simplified by reducing the selection to three robots. Each of the three had a different coordinate system, drive system, articulation, and controller capability. The three robots, each having different features were chosen so that the advantages and disadvantages of each feature can be compared for this particular application.

The three robots were: GMF M-1A, GMF S-110R and the Cincinnati Milacron T-3. The GMF M-1A is a cylindrical coordinate type of robot capable of up to five-axes of coordinated motion. The GMF S-110R is an articulated robot capable of five axes of coordinate motion. Finally, the Cincinnati Milacron (or CM) T3 robot is a jointed arm robot capable of six axes of coordinated motion. Each of these three robots have their strong points and their weak points.

The components discussed in the first part of this chapter were applicable to any of the three robots which is why the features of the work cell were given in generic terms. It would be impossible to give specific dimensions or to design the components without knowing which robot was going to be used.

For comparing each of the three robots, the six main categories examined were: ease of implementation, cost, usability, maintainability, machine familiarity, and future application adaptability.

On the next several pages are the comparison tables of each of the three robots for the above six categories. The comparisons were done on both qualitative and quantitative terms. Several items of all three robots were comparable and so stated. Layout drawings for each of the three robots are provided in Appendix A. Also shown in Appendix A is the work envelope profile of each robot in relation to the basket.

TABLE 4a.: Ease Of Implementation

	S-110R	M-1A	T3
Work Envelope	Small and restricted, basket must be raised and tilted, rear of basket inaccessible	Covers basket well, needs a device to reach bottom of basket	Excellent coverage of basket,
End-eff. Requirements	Simple gripper needed, extension required to reach areas	Gripper with a vertical plunger which can reach into basket is needed	Only a very simple gripper is needed
Required Secondary Device	*- All secondary devices will be common to all 3 robots		
Peripheral Equipment Area Required	Controller : 2.0' x 2.3' => 4.67 ft <sup>2</sup>	Controller : 2.0' x 2.3' => 4.67 ft <sup>2</sup>	Controller : => 8.3 ft <sup>2</sup>  Hydraulic Power Supp. => 17 ft <sup>2</sup>  Electrical Power Supp. => 3.4 ft <sup>2</sup>

Table 4b.: Cost

	S-110R	M-1A	T3
Base Robot w/ Necessary Options	\$ 47.5K	\$ 66.8K w/ Extended Z-Stroke \$ 53.9K Std.	\$ 98K
End-Eff. Cost (Relative)	Simple, Median Cost	Most Involved, Most Costly	Least Invol. Least Costly

Table 4c.: Usability

	S-110R	M-1A	T3
Ease of Change-over	Very easy, Articulation allows for simple tools, Large memory capacity	Easy, May need a more complicated end-eff., Large memory capacity	Very easy, Articulation allows for simple tools, Available w/ cassette mem.
Software Support	One palletizing program avail.	Three palletizing programs avail.	No palletizing software avail.
Articulation	Advanced articulation makes programming difficult to understand	Programming is easy to understand since cylindrical coord. robot	Difficult to program, too advanced articulation

Table 4d.: Maintainability

	S-110R	M-1A	T3
System Complexity	DC Servomotors, Chain/Sprocket drives, Brush maintenance required	AC brushless servomotors, High reliability	Complicated hydraulic circuitry w/ electrical control sys., outdated & unreliable technology
Robots In-house?	Several to be delivered as of 9/85	Approx. 15 robot in production	Two robots in production
Vendor Support	Trouble shoot w/ modem, local rep. available	Trouble shoot w/ modem, local rep. available	No local rep.

Table 4e.: In-House Audit

	S-110R	M-1A	T3
Engineering Staff	In-House tech. expertise; always use GMF; easy to program	In-House tech. expertise; always use GMF; easy to program; very durable	Programming language lacking; no local supp.
Maintenance Personnel	Full electrical system preferred since only one skilled trade required	Full electrical systems preferred since only one skilled trade required	Two skilled trades required; complicated interaction between hyd. and elec. sys

Table 4f.: Future Application/Flexibility

	S-110R	M-1A	T3
Changes in Product (System)	System is very adaptable	System is adaptable, but will need to rework end-effector	System is very adapt., very high load capacity
Flexibility Outside of Cell	Limited due to small and unusual work envelope	Very adaptable for simpler applications	Very adap. due to large work envel. and high capacity

### The Selected Robot

By comparing the information provided in the tables and the drawings(see Appendix A) for each of the robots, it was decided that the GMF M-1A robot would be most suitable for this application. The following are the main features of the GMF M-1A robot that made it most suitable for this particular application.

- The robot was median in cost
- Preprogrammed palletizing software package was available.
- The robot had an easy to use control system and simple work envelope.
- Several of these robots are already in use at Rochester Products.
- It had the most accurate and reliable drive system.
- The robot had the necessary wrist capabilities to ensure the canisters are packed in a linear fashion.
- The work envelope was well matched to the basket although a more sophisticated end-effector was needed to reach into the basket.

Now that the robot is selected and the overall layout derived, enough information is available to design the end-effector. Chapter VI thoroughly discusses the design of the end-effector.



## CHAPTER VI: END-EFFECTOR

The first part of this chapter covers general end-effector design considerations. The second part of this chapter covers the design of the end-effector used for this project.

### Chapter VI.a : OVERVIEW

The purpose of this OVERVIEW section is to review end-effector design considerations giving the reader a better understanding of the features incorporated in this project's final design. The topics discussed are general considerations, payload capacity, work envelope considerations, material selection and maintainability.

#### General Considerations

A designer should bear in mind that the robot has been designed in a general manner which ensures that it will be flexible to handle a variety of tasks. To compensate for this generality, it is necessary to design the end-effector solely for a specific application. In other words, design the end-effector to handle the specific task, such as loading canisters.{36} The designer should be aware that a tremendous amount of time and effort, put into the design of a robot, can be easily negated by a poorly designed end-effector.{37}

The end-effector should be designed for production use as opposed to a laboratory application. The end-effector should be designed and built rugged enough to withstand the industrial environment.{38}

Many robotic applications exist which require the robot to do more than one job. If this is the case, the designer needs to determine if the two tasks are compatible. Secondly, the designer needs to determine if both tasks can be handled by the same end-effector. For this project, the end-effector will load the canister and the separator trays into the basket (explained later in this chapter).

#### Gripping

How the end-effector grips the part is an important consideration for many robotic applications. First, the designer should consider all forces exerted on the end-effector. A robot is dynamic, thus a grasped part will exert a dynamic force on the gripper while the robot is in motion. As a rule of thumb, the

dynamic force is twice the weight of the part. For example, a 1-pound payload will exert approximately 2 pounds of force onto the end-effector when the robot is in motion.{39}

Once the dynamic force is known, it is necessary to determine how much force the end-effector must produce to hold the part. The required gripping force depends on several parameters but most importantly on the gripping configuration. It is best to grasp a part so that the dynamic forces are exerted against the structure of the gripper, minimizing the friction force required to hold the part in place. For example, suppose an end-effector is holding a part while accelerating through space as shown in Figure 15. In 15a, the friction force needed to hold the part is twice the weight of the part. In 15b, no friction force is needed to hold the part in place. The optimum configuration depends on the weight of the part and the magnitude of the acceleration, both of which should be calculated.{40} Other parameters which affect the required gripping force include the coefficient of friction and the part geometry.

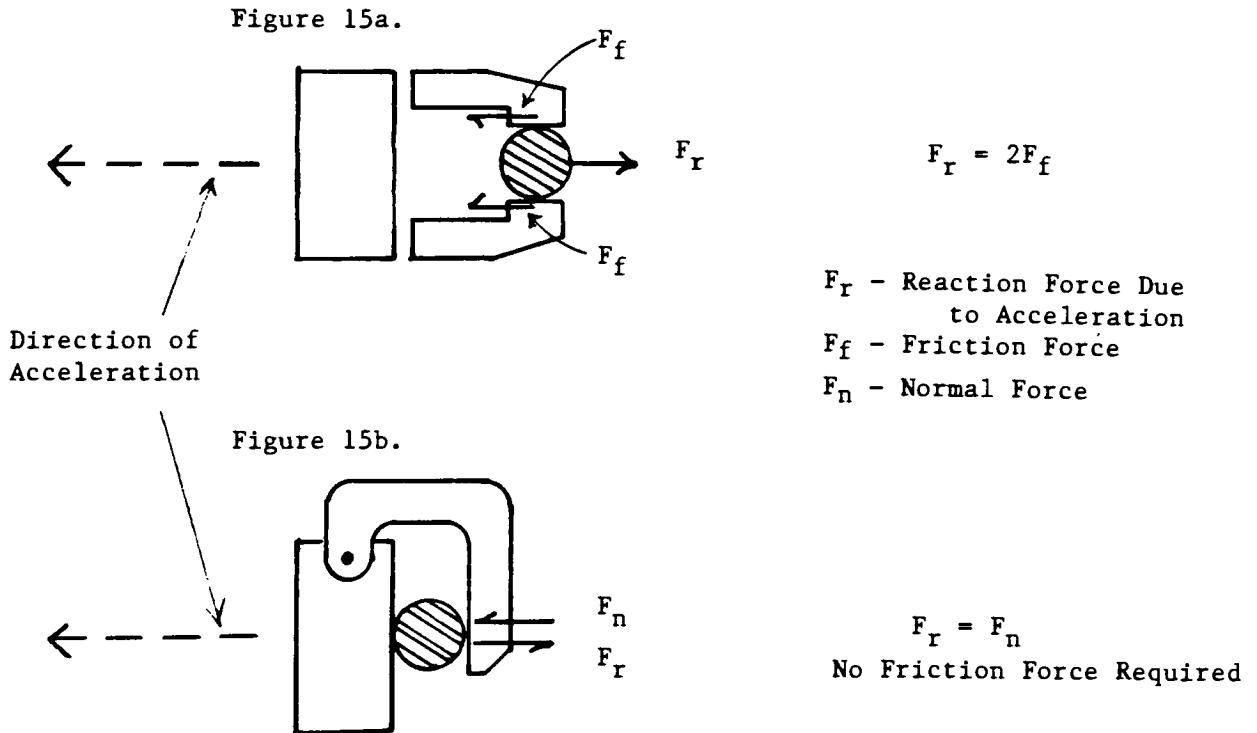


Figure 15: Different Gripping Configurations Require Different Friction Forces While Accelerating in the Same Direction at the Same Rate (effects of gravity omitted for the sake of clarity)

The necessary normal force can be derived from the calculated value of the required friction force. Once this force is known, a check should be done to ensure that the normal force does not damage the part. When gripping the part with metal jaws, minor scratches should be acceptable. If not, the gripper should have soft non-marking pads made from either rubber or polyurethane. Metal grippers have the advantage over rubber grippers offering a more positive grip (bite) and higher wear resistance.{41} The number of parts the end-effector handles should be considered since it influences the end-effector design. For example, if the robot will be required to handle a large number of parts, the designer must be sure that the contact surfaces are durable.{42}

Gripping cylindrical parts have several advantages. Grasping a part by either the inner-diameter or the outer-diameter offers good repeatability and adds a compliant quality to the end-effector. In other words, the grasping action forces the part to align into the gripper (compliance) and thus the robot will know exactly where the part is (repeatability). This helps tremendously in minimizing the complexity of the work cell.{43}

### Payload Capacity

The robot's working payload should always be of concern. The weight of the end-effector decreases the useful payload capacity of the robot. For example, if a designer is using a robot with a 50 lb. payload capacity, the robot will have difficulty lifting a 30 lb. object if the end-effector weighs 25 lb. The location of the center of gravity of the end-effector is also important. The payload capacity of the robot is often given at the face of the mounting plate where the end-effector attaches to the robot's wrist. If the center of gravity of the end-effector is displaced from the mounting plate, exerting a moment on the axes, the robot may not be able to handle the manufacturer's maximum specified load.{44}

### Work Envelope

The end-effector does not change the shape of the work envelope, but rather displaces it. This has the greatest impact on a robotic work cell which is already in place. A new end-effector may displace the work envelope enough to make certain areas unattainable, but this displacement may allow the robot to access areas which it might not have been able to reach previously.{45}

## Material Selection

If high durability and strength are of importance, and the robot has adequate payload capacity, the end-effector should be made of steel. If weight is the main concern and/or strength is a lesser concern, aluminum is the best choice. Since aluminum is not as durable as steel, additional measures need to be taken to ensure the end-effector will withstand an industrial environment. Steel threaded insets should be used to prevent the bolts from stripping the soft aluminum. Interfacing surfaces should be hardened to minimize wear and deformation. It is a good idea to use a combination of both steel and aluminum in the end-effector to exploit the advantageous qualities of each material.{46}

## Maintainability

The ability of the end-effector to be repaired quickly is of great importance. The longer the work cell is down due to end-effector repairs, the less productive it becomes. A basic means of implementing a successful production tool is to minimize the quantity and the types of fasteners used. Also, critical bolts should not be hidden. Any component(s) which fails frequently, should be readily accessible and spares should be on hand. Beyond this, if the robot and end-effector are used in a critical production area where down time cannot be tolerated, it is wise to have a spare end-effector on hand.{47}

## Chapter VI.b : END-EFFECTOR DESIGN FOR PACKING CANISTERS

The main areas of discussion are assessment of the end-effector task, the robot/end-effector interface, examination of how the canister will be gripped, the gripper design, the separator tray pick up device, and the compliance device. Finally, details such as material selection, weight and center of mass calculations, dynamic force calculations, and general features are discussed.

### Task Assessment

For this application, a dual task end-effector is required. Its primary purpose is to load the canisters into the basket. Its secondary purpose is to place the separator trays into the basket. This dual task end-effector simplifies the design of the work cell and better utilizes the robot.

Considering the primary task first, the end-effector must meet the following design requirements. First, it must provide the required "reach" capabilities to load the canisters on the bottom of the basket. Second, the end-effector must be able to handle two canisters simultaneously. The reason for this relates to the cycle time constraints and the need to test two canisters simultaneously (see page 26). Third, the end-effector must be able to grasp and release each of the two canisters independently. This feature is necessary in the event that only one of the two canisters tested is found to be defective. The end-effector must dispose of the defective canister while holding onto the other canister.

For the secondary task, placing the separator trays into the basket, the end-effector must be designed to keep the tray stable while the robot is moving it to the basket and placing it in. If the tray is unstable (not firmly grasped) its position relative to the end-effector may change. If this happens, the tray will collide with the side of the basket upon placement.

To recap, the end-effector must be able to:

- Pack the canisters on the bottom of the basket
- Handle two canisters simultaneously
- Grasp and release each of the two canisters independently
- Keep the separator tray stable while the robot is moving it

## Interfacing with the Selected Robot

The selected robot was the GMF M-1A cylindrical coordinate robot. For this application, the wrist was required to yaw. The yaw feature is utilized to align the canister pairs with the parts nest in the separator tray. This is shown in Figure 16a. The only wrist option which offers the required yaw capability is the F2 wrist which is shown in Figure 16b.

Next to be considered was how the end-effector would reach into the basket. The end-effector needs to extend downwards, away from the wrist, in order to place the canisters in the lower section of the basket. The initial concept was to use an extension arm to reach down into the basket as shown in Figure 17.

The standard Z-stroke (21.6") of the GMF M1A robot was inadequate to pack both the top and bottom canisters using the concept shown in Figure 17. The extended Z-stroke (52.6") version of the robot cost an addition \$10,000 and was not cost justifiable.

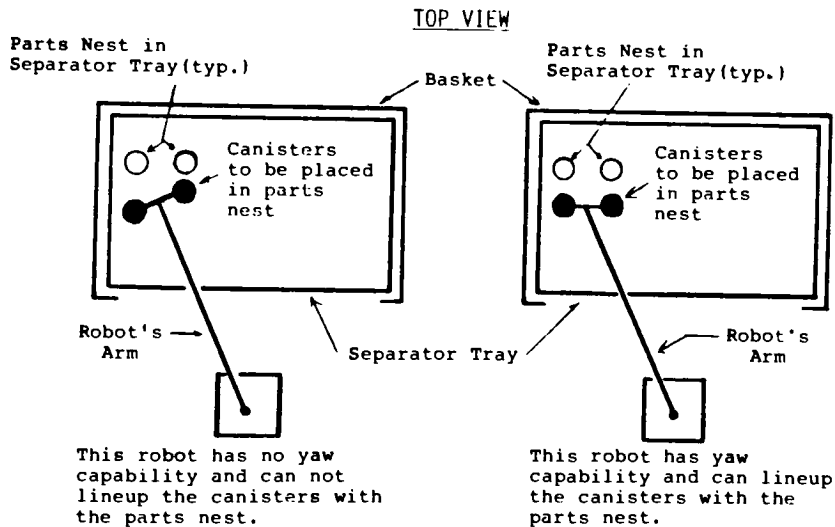


Figure 16a: Yaw capability utilized to lineup canisters with the parts nest

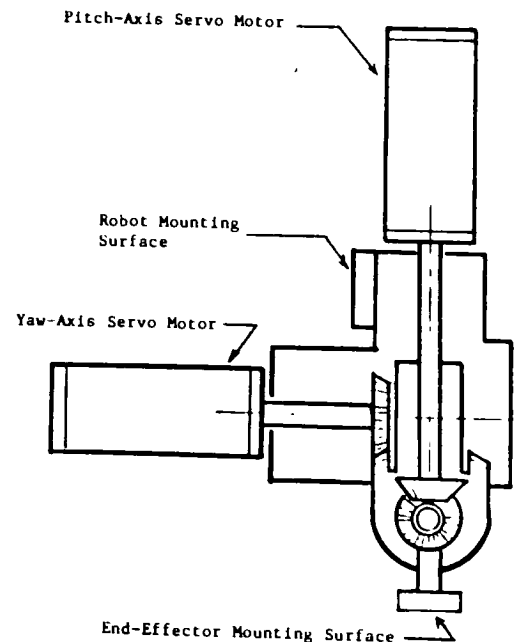


Figure 16b. F2 Wrist Option For GMF M-1A Robot

After deciding that the end-effector design should be such that it could pack both the top and the bottom of the basket without the need of the extended Z-stroke, several ideas were considered. It was decided that the dynamic capability of the robot's wrist should be utilized.

The initial sketch of the end-effector is shown in Figure 18. Notice that the end-effector is symmetrical, and is mounted off-center resulting in a long "reach" arm and a short "reach" arm. The long arm is for packing the lower layers of the basket and the short arm is for packing the upper layers of the basket. Figure 18 illustrates how the wrist manipulates the end-effector to pack either the upper layer or the lower layer of the basket. The manipulation is shown in four steps. In the first step, the end-effector is positioned to pack the lower portions of the basket. In the last step, the end-effector is positioned to pack the upper portions. For added clarity, both the front and side views of the end-effector are shown.

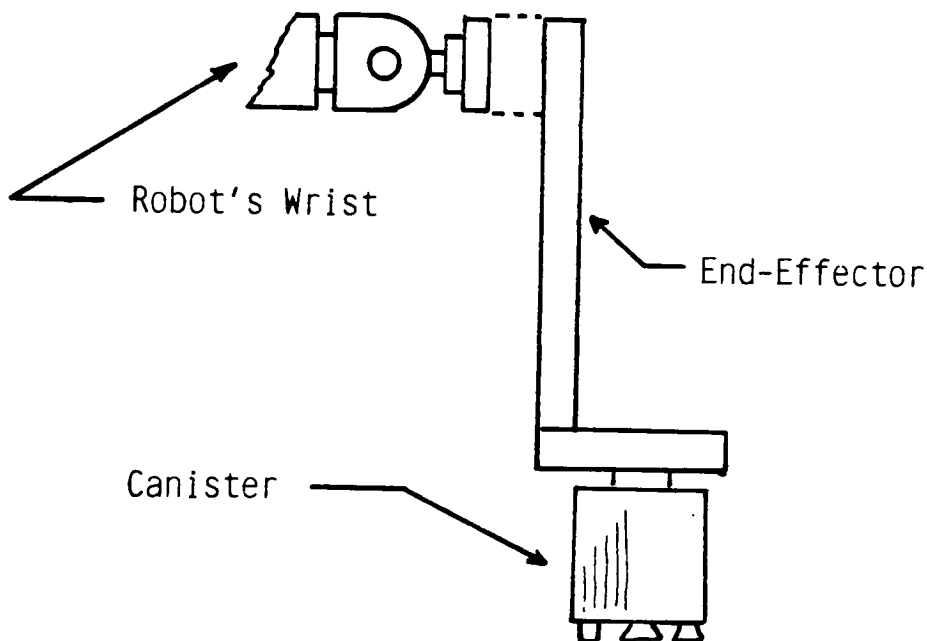
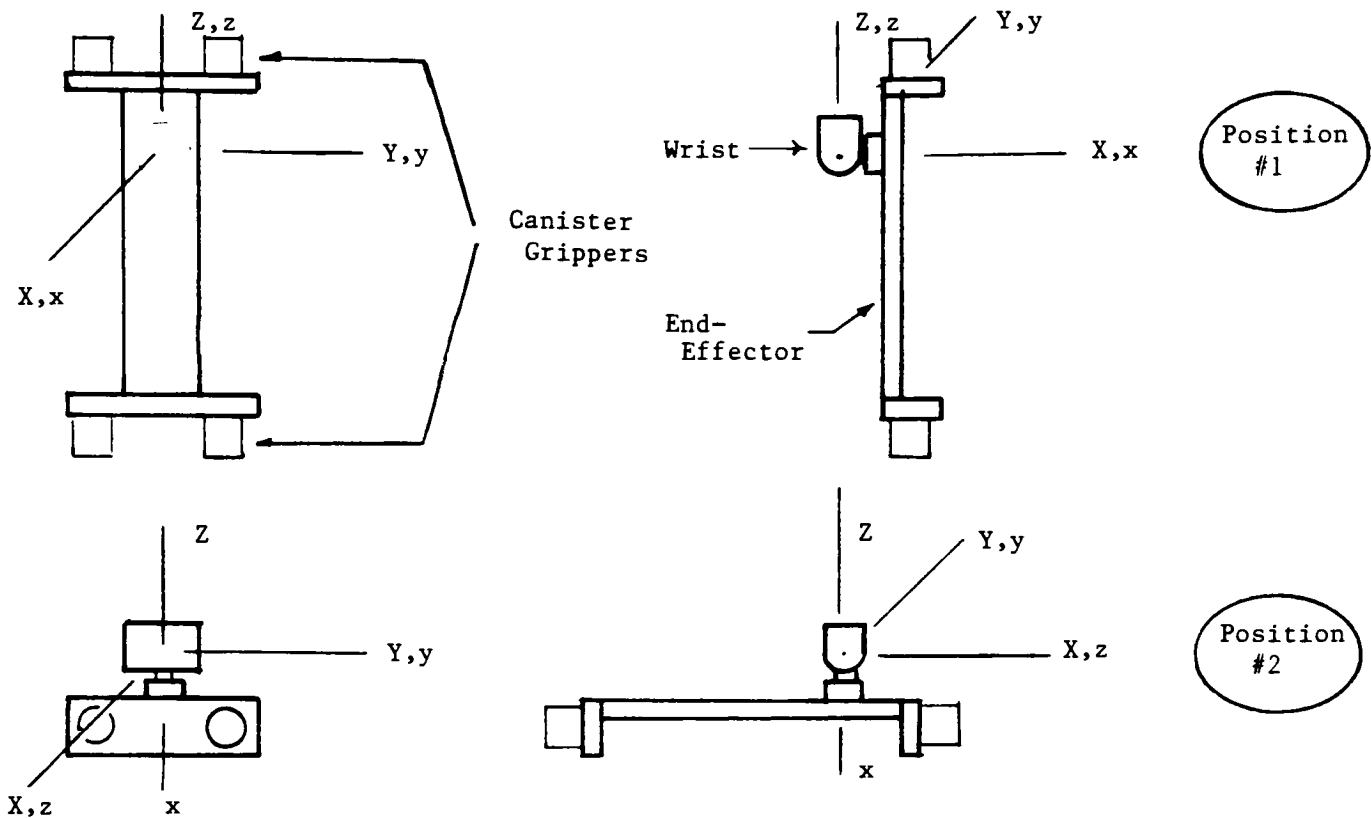


Figure 17: Initial Design to "reach" into the Basket



#### MOTIONS OF THE END-EFFECTOR

Note: Axis XYZ is attached to the wrist

Axis xyz is attached to the end-effector

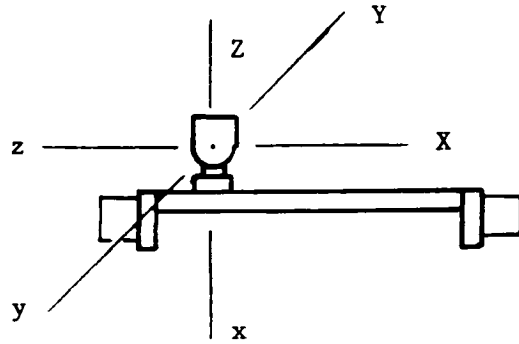
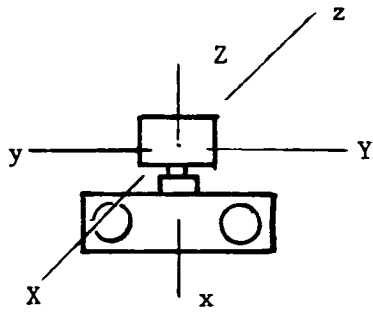
The origins of XYZ and xyz are coincident on the wrist

Position #1: Axes XYZ and xyz are coincident;  
This position is for packing the lower  
layers of the basket

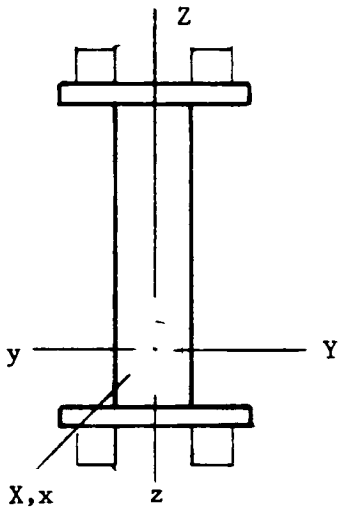
Position #2: The end-effector rotates  $+90^\circ$  about the Y-axis

Figure 18: Wrist Manipulation Sequence to  
Reposition the End-Effector to  
Pack the Upper Layers of the Basket

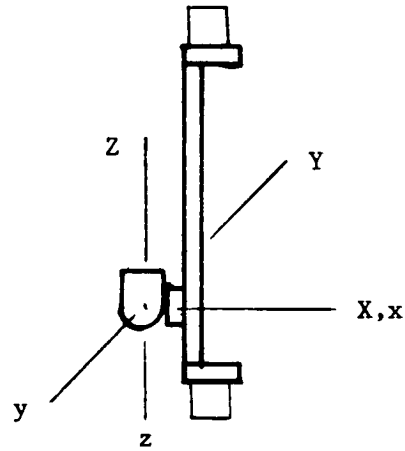




Position  
#3



FRONT VIEW



SIDE VIEW

Position  
#4

Position #3: The end-effector rotates  $-180^\circ$  about the Z-axis

Position #4: The end-effector rotates  $-90^\circ$  about the Y-axis;  
This position is for packing the upper layers of the basket.

Figure 18: Wrist Manipulation Sequence to Reposition the End-Effector to Pack the Upper Layers of the Basket

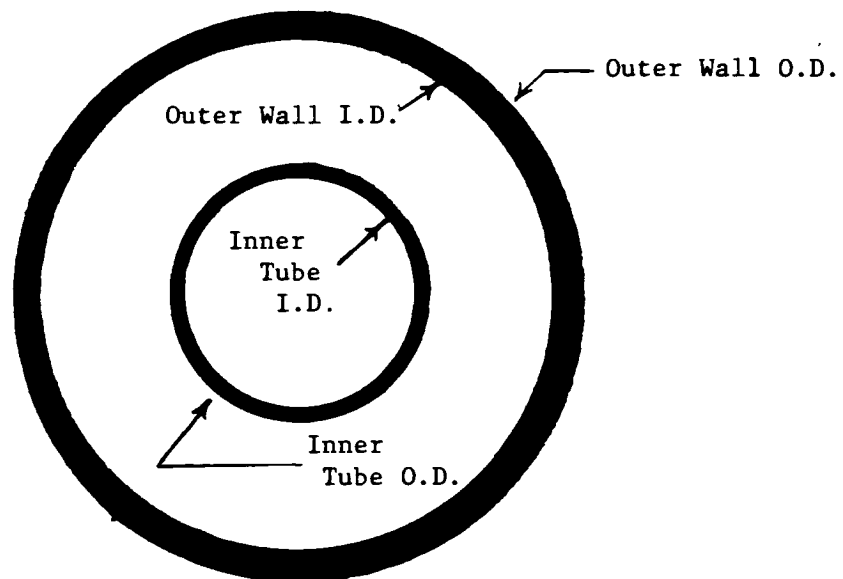
## Grasping the Canister

One of the first things considered was where should the end-effector grasp the canister. To ensure that the components on the closed end of the canisters are not damaged and to minimize the amount of manipulation required by the robot, the canisters were to be handled with the open-end of the canister always remaining up. Thus the four possible locations to grasp the canisters are(Figure 19):

- The Outer Wall's Outer Diameter
- The Outer Wall's Inner Diameter
- The Inner Tube's Outer Diameter
- The Inner Tube's Inner Diameter

The outer wall's OD was a poor choice because the gripper mechanism of the end-effector must extend beyond the periphery of the canister. This has two negative aspects in that it will be excessively heavy and it decreases the available clearance. It adds excessive weight to the end-effector because the actual gripping mechanisms needed to be larger than the two canisters (greater than 12 inches).

Although grasping the canister on either the outer wall's ID or the inner tube's OD eliminated the clearance problem, the design would still be excessively heavy for the same reason given above. Thus, by the process of elimination, the best place to grasp the canister is on the inner tube's inner diameter.



Bottom View(Open End) of Canister

Figure 19: Four Areas to Grasp the Canister

## Gripper Design

A variety of mechanisms were available for grasping the canister. Bear in mind that whichever method was chosen, four mechanisms would be required on the end-effector (two on both the short and the long end). The three best types of mechanisms for this application were (Figure 20) :

- Toggle Jaws
- Expandable Collet
- Inflatable Bellows

The toggle jaw mechanism is a very popular device in material handling. This mechanism is usually powered by a pneumatic cylinder, and opens and closes to positions determined by the geometry of the mechanism. The advantages of a toggle jaw were: strong positive grip, good wear capabilities and accurate movement for precise applications. The disadvantages for this application were: excessive weight of four pneumatic cylinders (one for each gripper), complicated fabrication, complicated repair and maintenance, poor passive compliance, and uneven pressure distribution. Because of these disadvantages the toggle jaw was not considered.

An expandable collet uses a pneumatic cylinder to compress a rubber ring causing the sides to expand. The advantages of this type of mechanism were : even pressure distribution, easy to fabricate, and good passive compliance. The main disadvantage of this type of gripper was that it required four pneumatic cylinders, thus creating a weight problem.

Finally, the inflatable bellows is a gripping device which has no moving parts and bellows expands when it is pressurized. The advantages of this type gripper are : even pressure distribution, ease of fabrication, good passive compliance, easy to maintain, and no need for pneumatic cylinders (thus allowing for a light weight design). Because of these advantages, the bellows was chosen to be the gripper for this application.

The design of the bellows has several features which are worth commenting on. See Figure B-4 of the Working Drawings for clarity of the explanations. The wall thickness was determined by trial and error. As crude as this method was, it proved to be quite successful. The initial wall thickness was decided on by discussing the problem with several engineers at Rochester Products who have experience in designing such bellows.

The bellows was made of polyurethane which is durable and highly elastic. Also, the cure temperature is higher than the temperature of the canisters coming out of the molding machine, thus the bellows will not break down when it comes in contact with the hot canisters. Finally, the polyurethane is relatively inexpensive, readily available, and easy to work with.

The bellows has a long bolt traveling down its center to prevent the bellows from elongating while it is being inflated. Without this bolt, the bellows would stretch axially as opposed to expanding radially as required. The reason for this is that the hoop stress is approximately twice the longitudinal stress.

The bellows' geometry had two "designed in" passive compliance features which allow for slight misalignments when the robot attempts to pick up the canisters. The tip of the bellows was tapered allowing it to "thread" the canister if not correctly positioned. The second taper near the base of the bellows (see Figure A-4 of Appendix A) assured that the canisters had good radial and axial repeatability (assuring the canister would always be in the same place after it has been picked up). Also, the deflated diameter of the bellows is 1/8 inch less than the inner diameter of the inner tube. This allowed significant leeway for variation in position and the inner tube's inner diameter.

Although the canisters are light in weight, they need to be firmly gripped. The rings on the outside of the bellows (Figure A-4) allowed for additional gripping firmness. The length of the bellows was also longer than needed. This was done to ensure the gripper could grasp a canister which had a severe case of short shot.

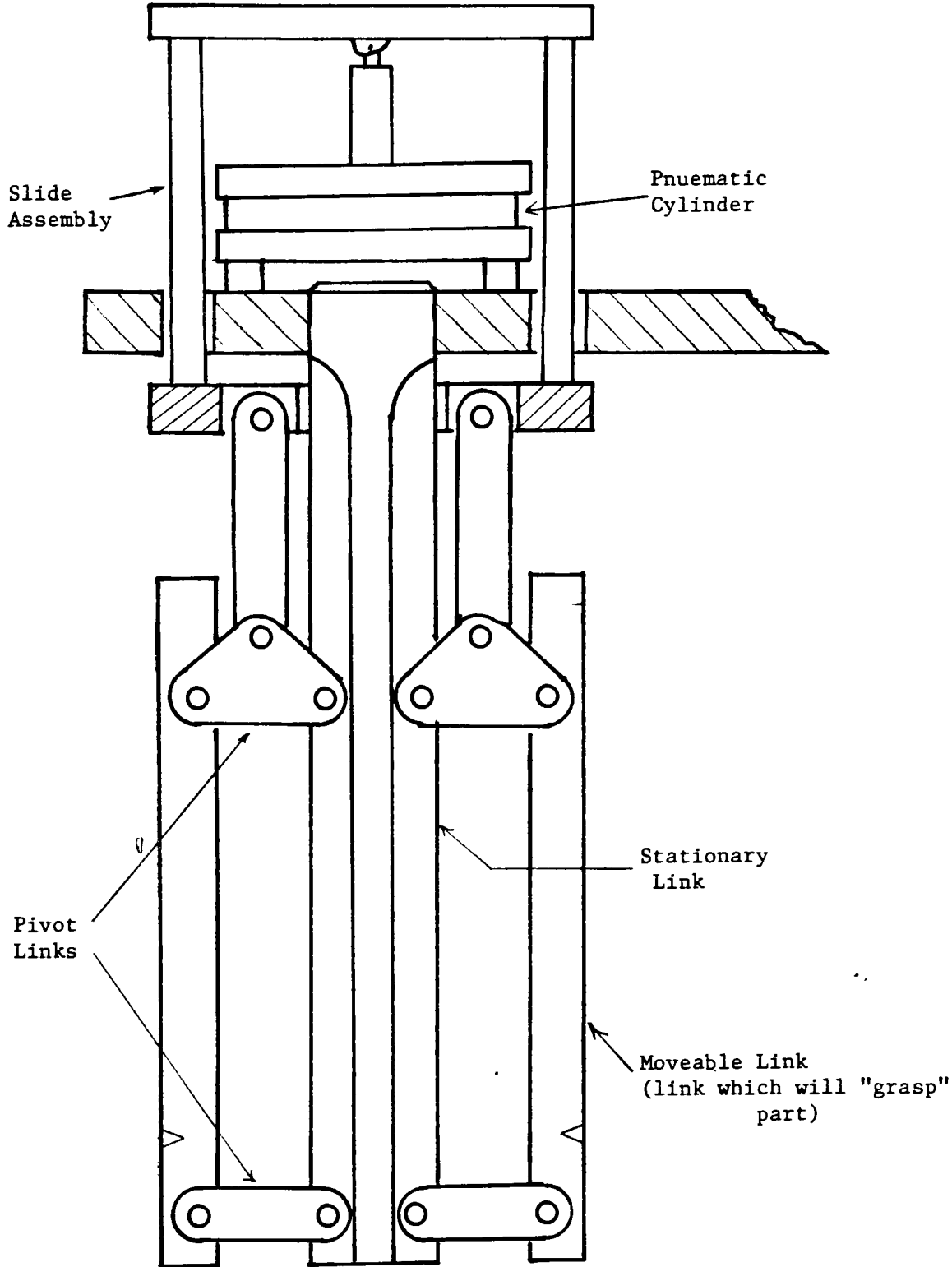


Figure 20a: TOGGLE MECHANISM TYPE END-EFFECTOR

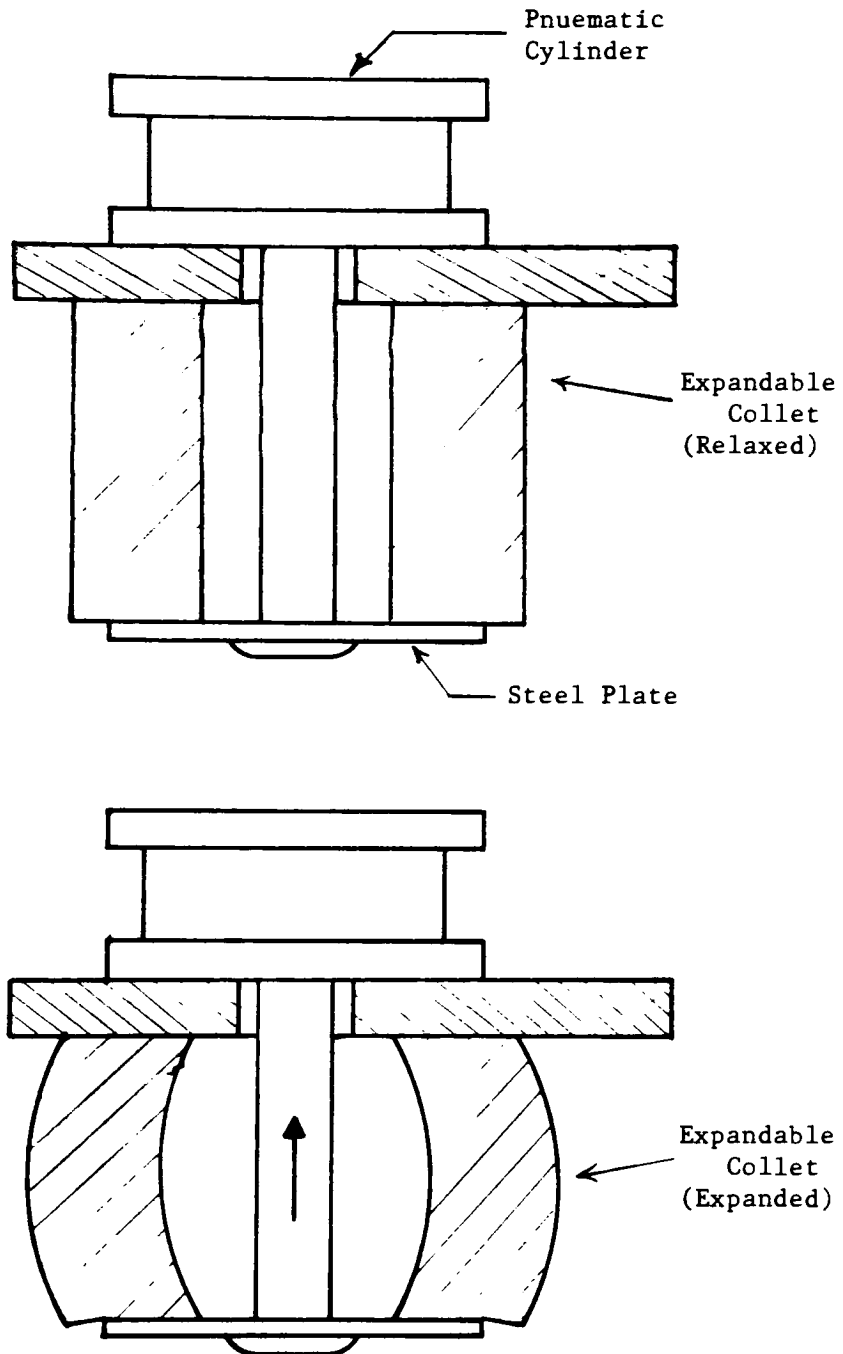


Figure 20b: EXPANDABLE COLLET TYPE END-EFFECTOR

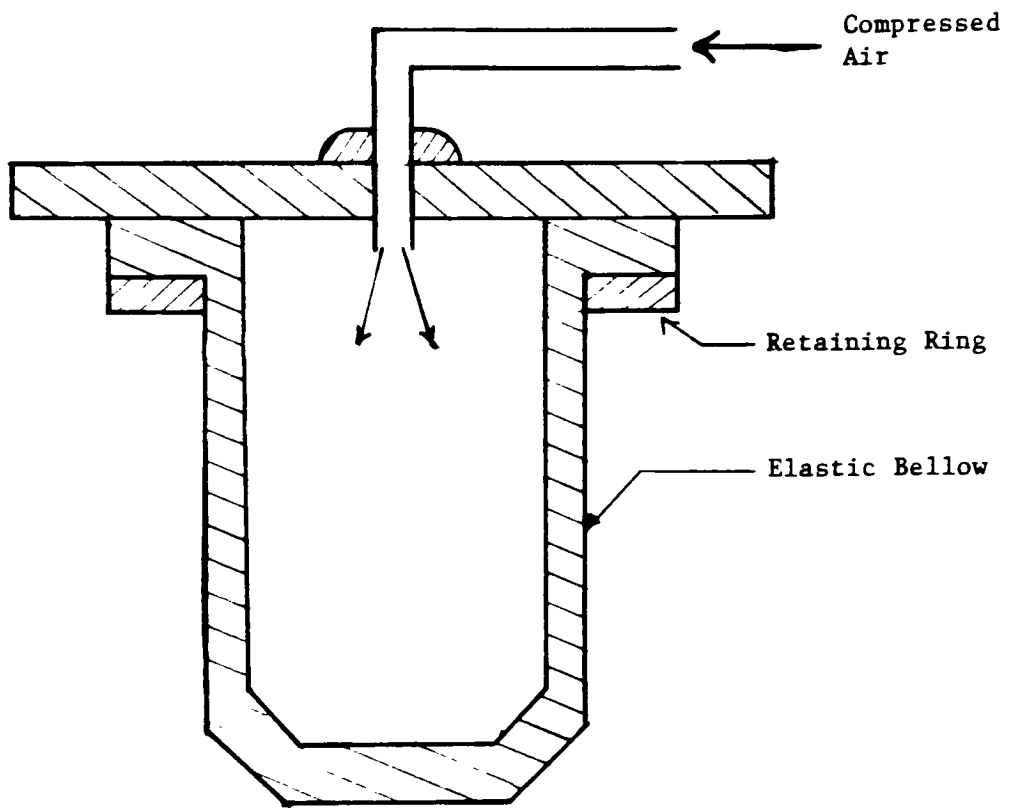


Figure 20c: BELLOWS TYPE END-EFFECTOR

## Tray Pick-up Device

As mentioned earlier, the end-effector had two purposes. The first was to pack the canisters and the second was to pick up and place the separator trays. The design of the separator tray is beyond the scope of this project. It was, however, assumed that the tray would be a vacuum-form plastic part with steel reinforcements for added rigidity. The tray would have recesses and rises which would hold the canisters in place. The empty trays would be stackable for easy handling. Also it was assumed that the tray would be designed to match the design of the end-effector.

When generating ideas on how to pick up the trays, it was important to keep in mind their size. The trays are 50 inches wide by 40 inches deep. The tray must be stable while the robot is moving them. An excellent way to ensure the stability is to have the contact points (between the tray and the end-effector) as far apart as possible. From the initial sketches shown above in Figure 18, this was best accomplished by positioning the end-effector as shown in Figure 21.

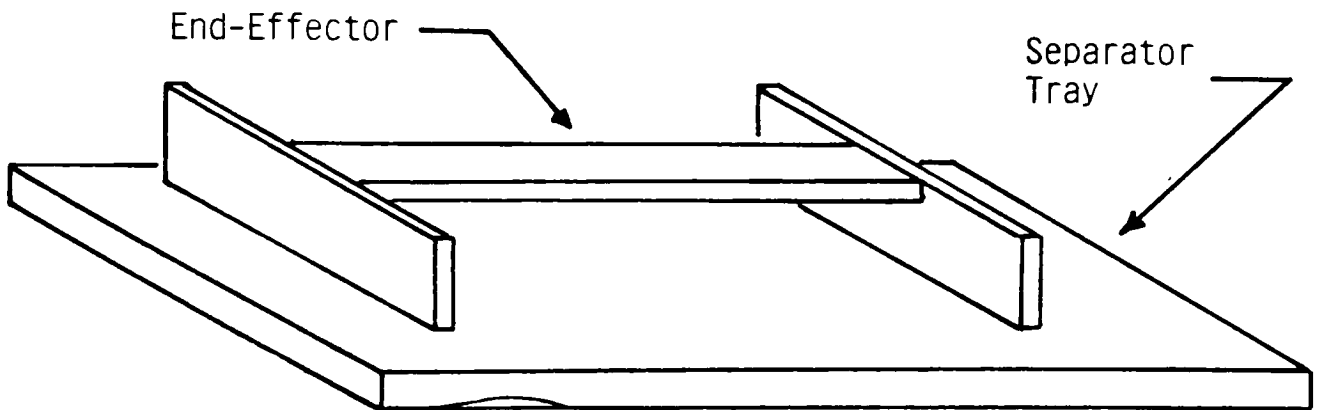


Figure 21: End-effector's Position to Pick Up the Separator Tray



After considering several viable alternatives on how to grasp the tray, it was decided to use two opposed pneumatic cylinders. Shot pins would be attached to the rod of each cylinder which would hook under tabs provided on the separator tray as shown in Figure 22. Bear in mind, that due to reasons of cycle time, the first tray would be put in place by the set-up man and the robot will not have to place it in.

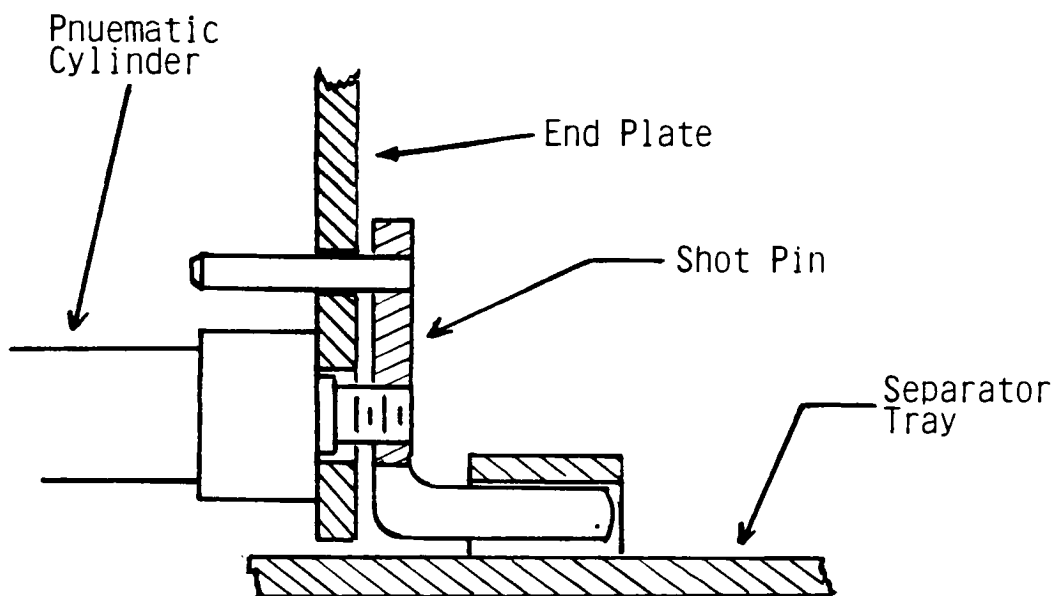


Figure 22: Shot Pin For Picking Up Separator Tray

## Compliance Device

In the event of a collision, a compliance device would minimize or prevent damage from occurring to either the robot, the end-effector, or the object which the robot collided with. Damage to either the robot or the end-effector would be costly for two reasons. The first is the cost of repair or replacing the damaged components. The hidden cost is the loss of production time.

The compliance device provides a non-rigid interface between the robot's arm and the end-effector. It is very similar to the ski binding mechanism which keeps the skier's boot attached to the ski. When a certain force is applied to the binding in a detrimental direction, the ski binding will release. The same analogy is applied to the compliance device. The compliance device will release when a certain force is applied to the end-effector.

Not only does the compliance device prevent damage being imparted, it can also be equipped with microswitches which will electrically signal the controller that a collision has occurred and to shut the system down. Thus the compliance device acts as a time buffer providing the controller extra time to react to the collision signal.

The compliance device for this application has 6 degrees of freedom and is self-realigning. That is, if slightly displaced, the compliance device automatically moves back to the correct position. For good repeatability, the compliance device has no play under normal use.

Figure B-9 of the working drawings (see appendix B) shows a cross sectional view of the assembled compliance device. For reasons of weight, the compliance device is made of aluminum. The forward plate and centering cones, however, are made of steel, and the bearing surfaces are polished and hardened. This is done to minimize friction between the two surfaces (Figure B-8).

Notice how the centering plate and the post can rotate around, and move parallel to, the center line. This provides two degrees of freedom. The centering plate can also pivot around any one of the three centering cones providing two additional degrees of freedom. Finally, the centering plate can be moved in the direction normal to the face of the page and vertically parallel to the face of the page. This provides the last two degrees of freedom. The combination of these movements allow for the necessary 6 degrees of freedom.

The force exerted onto the centering plate by the springs causes the compliance device to realign. The spotfaces on the back side of the centering plate and on the front side of the back plate holds the springs in place. Using the dimensions of the parts of the compliance device, basic trigonometric

calculations were performed to ensure that no binding occurs during deflection. Ten tapered flat-head screws secured the compliance device to the robot's wrist, six are used to secure the adapter plate to the wrist and four to secure the back plate to the adapter plate.

### Materials, Weight and Center of Mass Calculations

The overall dimensions of the end-effector were based on the task requirements. The separator tray thickness was assumed to be 1 inch for these calculations. Using the separator tray's thickness, the height of the canister, the depth of the basket, and the wrist dimension, the necessary end-effector dimensions were derived. This was done for both the long and short sections of the end-effector (Appendix C).

After the initial end-effector design was derived, the weight and the center of mass were calculated (Appendix D). These calculations assured the designer that the GMF robot was able to hold the end-effector in place. The canister weight was not included because it is quite small compared to the weight of the end-effector.

The weight of the end-effector was 13.1 lb. The maximum capacity for the robot, using the F2 wrist, is 40 lb. Thus the robot has 27 lb. lift capacity. Since a separator tray would not weigh any more than 10 lb., the robot has plenty of payload capacity.

It was necessary to know the center of mass of the end-effector for several reasons. One reason was to find the static moment that the end-effector exerts on to the wrist. The resulting moment was found to be 7.0 ft-lbs. The torque capacity of the wrist is 14.8 ft-lbs which was more than adequate (Appendix D).

The center of mass was also used to find the necessary spring force needed to ensure the compliance device would not slip while the robot was moving at full speed. It was found that the each spring needed to exert 120 lb. of force on the centering plate (Appendix E).

Shown in Figures B-1 through B-9 (Appendix B) are the complete working drawings of the final end-effector design. The selected material for all of the components of the end-effector, except two, were aluminum. Aluminum was chosen because of its light weight and machinability. Lightening holes were provided in the extension arm to further reduce the weight. No lightening holes were added to the end-plates because it was felt that extra rigidity was of greater importance than weight conservation. The entire end-effector was assembled using tapered flat head screws which did not allow any movement between parts.

The overall success of the end-effector is discussed in the Summary of this text (Chapter VII). In Chapter VII, the testing of the bellows, the testing of the compliance device, and the overall design is discussed.

## CHAPTER VII: SUMMARY AND CONCLUSION

The objectives of this thesis were to conduct a literature search to support and guide the development of this project; to design a robotic work cell layout for the given application; and to design, build and test the end-effector which would be used in the work cell.

Although these objectives have been accomplished, much remains to be done before the cell can be implemented. Many items need to be designed and developed, and then the whole system needs to be integrated and debugged. The following are items needing further development, but are beyond the scope of this project : the test stand, the holding stand, the separator trays, the lifting device for the baskets, the canister handling device to deliver the canisters to the robot, and the controller system.

The results for this design and development effort, are listed below.

### LITERATURE SEARCH

- The literature search provided useful information which were incorporated into this project and are listed below.

#### System layout

- How to layout the separator tray.
- The process for selecting a robot.
- How to position the components.
- The need for flow chart considerations.
- The need for cycle time considerations.

#### End-effector

- The need for and design of a compliance device.
- The importance of the weight and the center of mass.
- The use of a dual purpose end-effector.
- The need for a durable and light weight design.
- The use of ideas on how to grip cylindrical parts.
- The use of tapered flat-head machine screws.

### SYSTEM LAYOUT

- The GMF M-1A robot is capable of reaching all points of the work cell.
- The collision area between the two robots is minimized.

- The test stand and reject basket are adjacent to one another to minimize the time the robot handles a rejected canister.
- One reject basket is shared by the two robots.
- All of the components in the work cell are perpendicular to the tangent of the robot's work envelope.
- Each of the two packing baskets are accessible from the main aisle allowing them to be quickly exchanged.

## END-EFFECTOR DESIGN

- Overall:

Since the end-effector was made of aluminum, it is both light weight and durable. Durability is very important since the end-effector will be used in an industrial environment. The majority of the bolts on the end-effector are located such that they are easily accessible which allows for quick change overs. After reviewing the completed end-effector, the author realized that gussets should have been used between the end plates and the extension arm. This would increase the rigidity of the end-plates.

- Bellows:

After one bellows was successfully molded, it was tested for rigidity. Using air pressure ranging from 5 to 15 psi, the bellows snugly grasped the canister. To check if the bellows could withstand a higher pressure, it was removed from the canister and inflated to 20 psi. The bellows successfully withstood this pressure and showed no visible signs of plastic deformation. Once fully assembled, it was realized that the mandrel inside the bellows was not necessary since the bellows itself is quite rigid. Elimination of the mandrel would reduce cost but not effect performance.

- Compliance Device:

The design of the compliance device was slightly altered during fabrication. The front plate was made of aluminum as opposed to steel as called for. Steel bushings were fabricated and force fitted into the front plate providing a hard surface for the centering cones to ride on.

Once the compliance device was assembled, it had the necessary six degrees-of-freedom. It did not, however, accurately realign because the bearing surfaces on the centering cones and the bushings were not polished. The unpolished surfaces caused excessive frictional forces which hampered the final centering motions of the device.

On the next five pages are photographs of the completed end-effector compliance device and canister. The last photograph show the canister being grasped by the bellows.

In conclusion the objectives of this thesis were met. A literature search was conducted to support the design of the robotics system, and the design and construction of the end-effector. The author also learned to use Rochester Products' CADAM system to develop all of the working drawings for this project. While working on this project, the writer also gained a practical knowledge of industrial operations. The final completion of the project is uncertain. This is due to Rochester Products's rapidly changing product line. Thus the future of the canister line is not clear at this time.

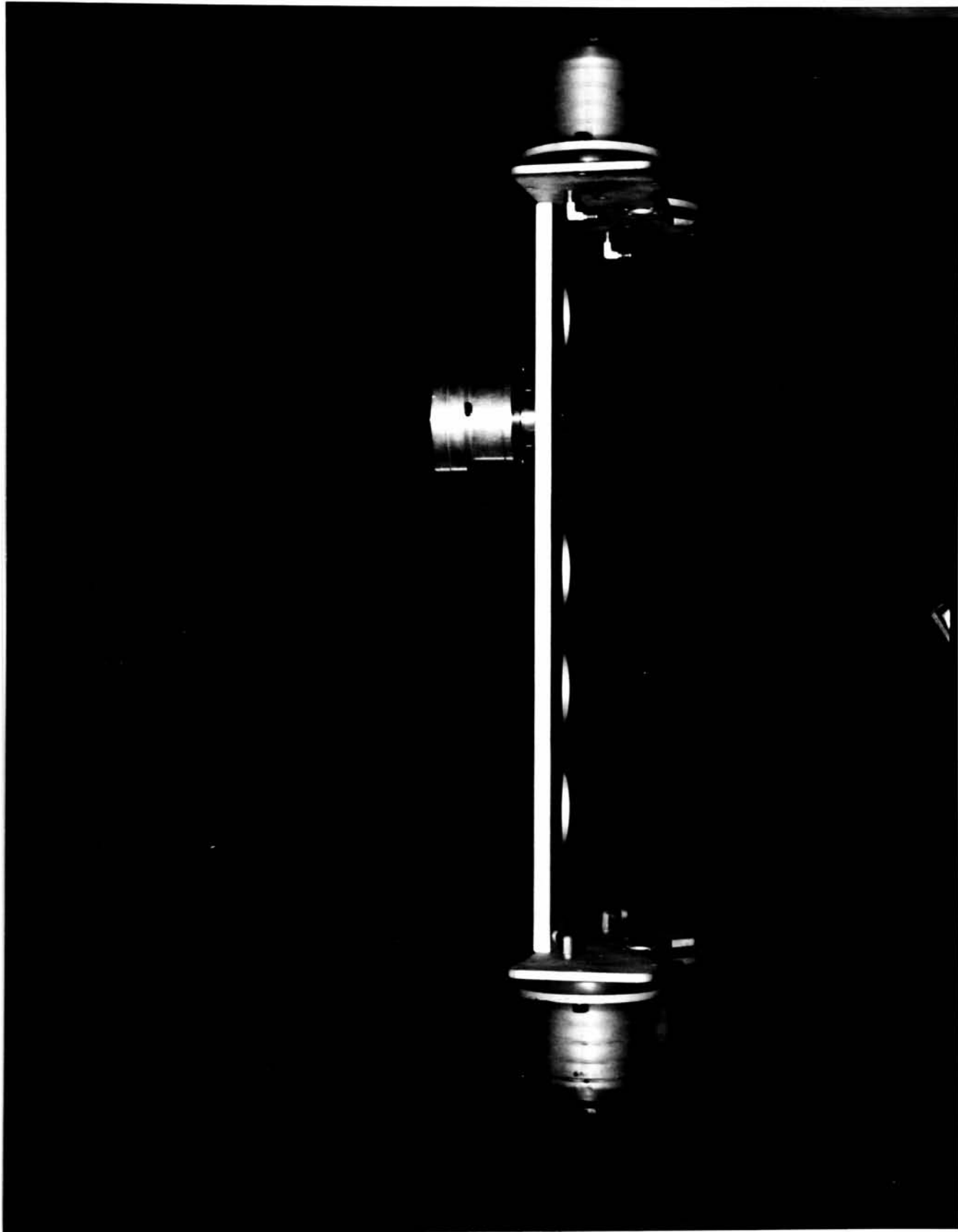


Figure 23, End-Effector, Front View



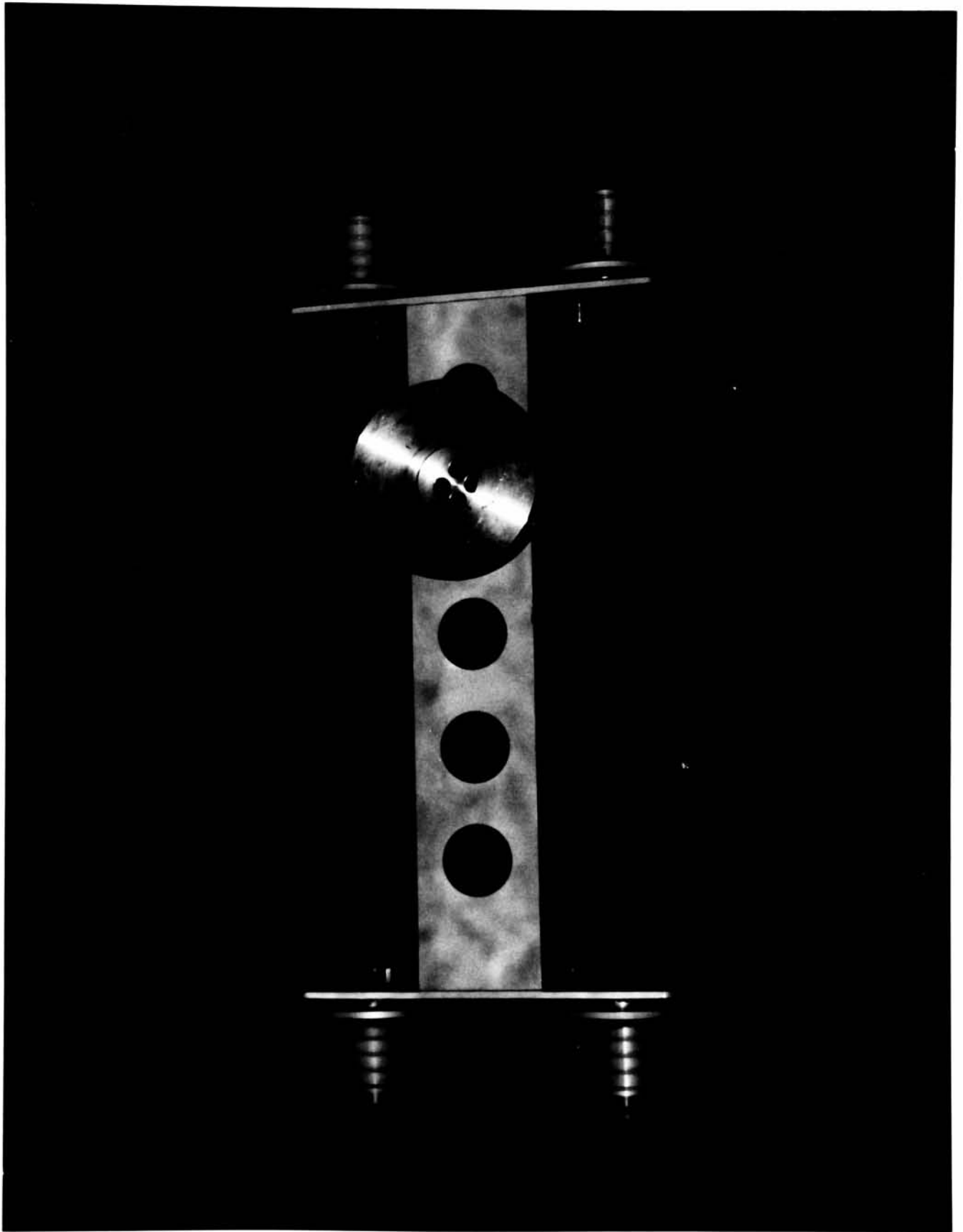


Figure 24: End-Effector, Side View

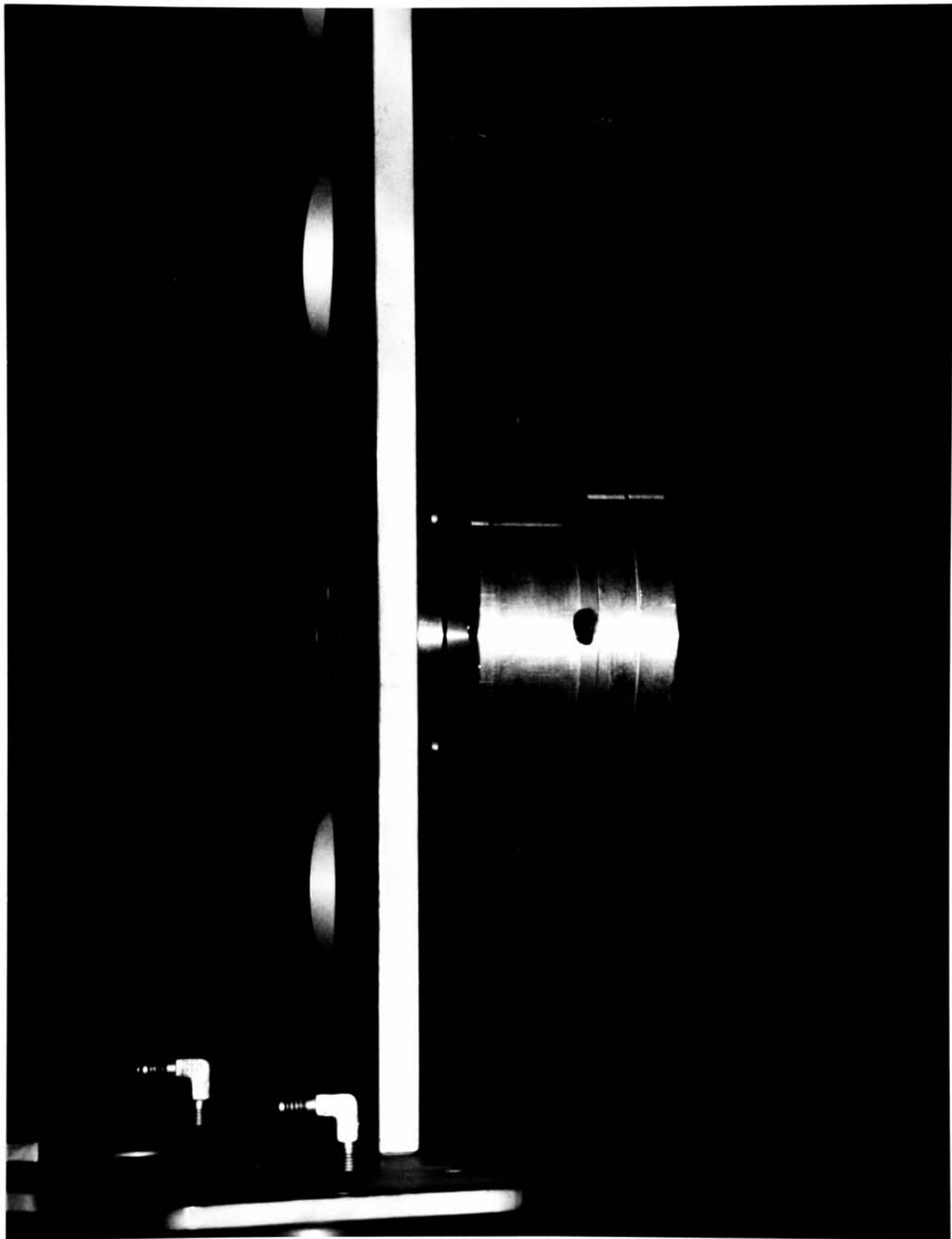


Figure 25: Compliance Device



Figure 26: Bellows

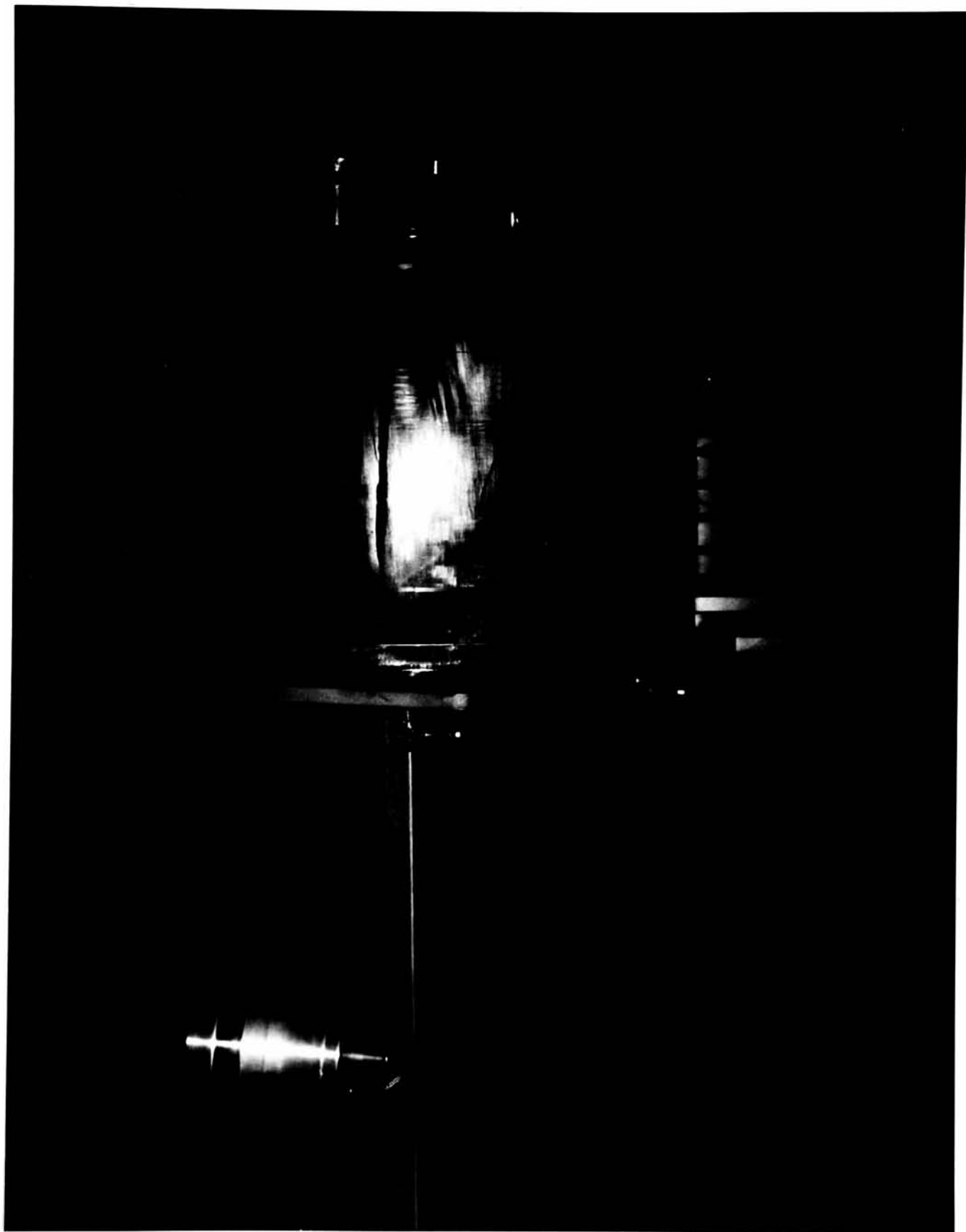


Figure 27: Bellow and Canister

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## APPENDICIES

Appendix A: Layouts and Work Envelopes For  
Selected Robots

B: Working Drawings

C: Sketches of Required Dimensions

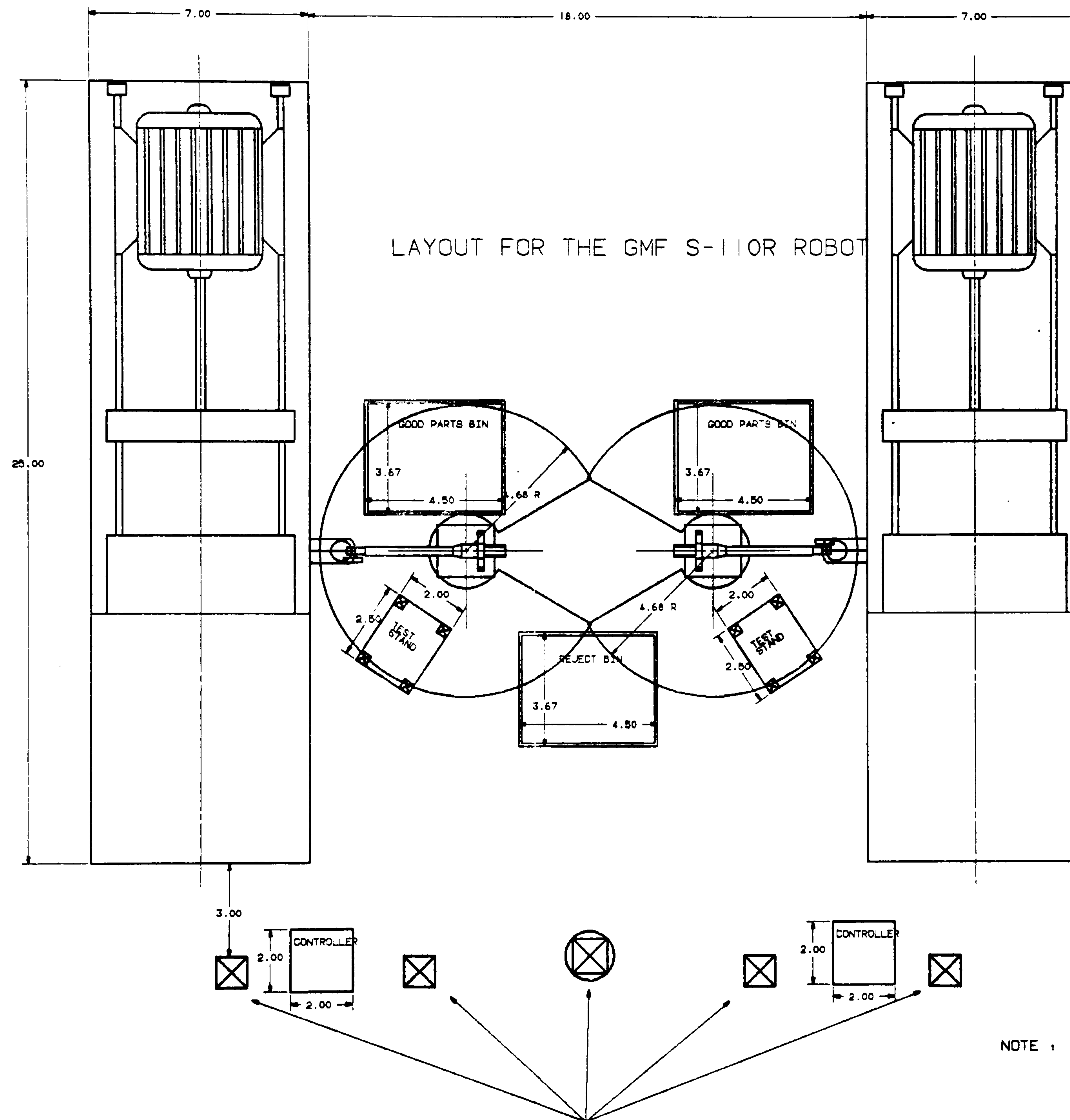
D: Weight and Center of Mass Calculations

E: Spring Force Calculations for the  
Compliance Device



## APPENDIX A

The layouts and work envelopes for the Cincinnati Milacron T3 robot, the GMF S-110R robot and the GMF M-1A robot are shown in this appendix. The drawings were developed so that the dimensions of each robot could be compared. The drawings were developed on Rochester Product's CADAM system and all features are to scale.



NOTE : DIMENSIONS ARE IN FEET

SUPPORT POSTS

FIGURE A-1: LAYOUT FOR GMF S-110R ROBOT

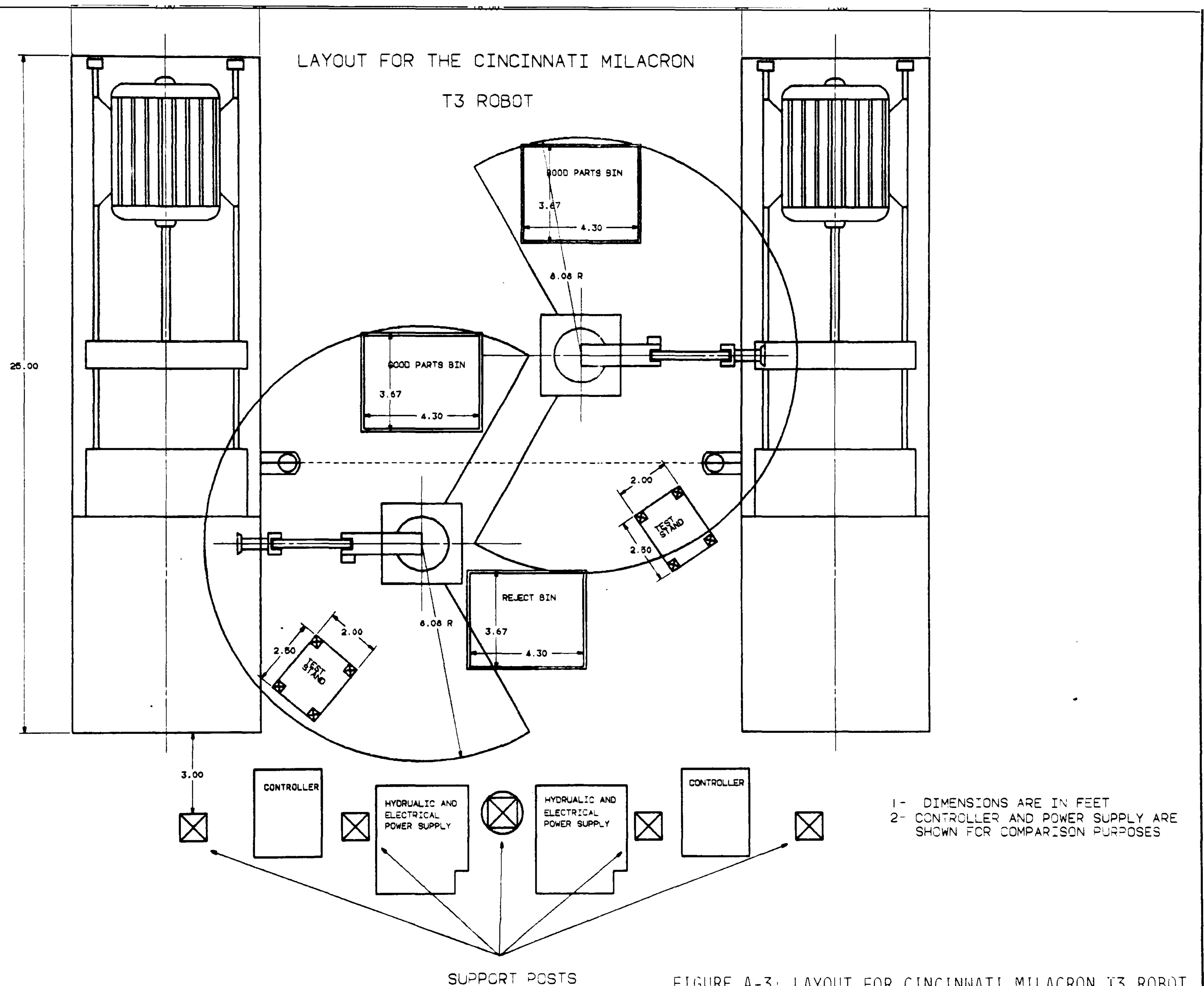


FIGURE A-3: LAYOUT FOR CINCINNATI MILACRON T3 ROBOT

WORK ENVELOPE FOR  
THE CINCINNATI MILACRON  
T3 ROBOT

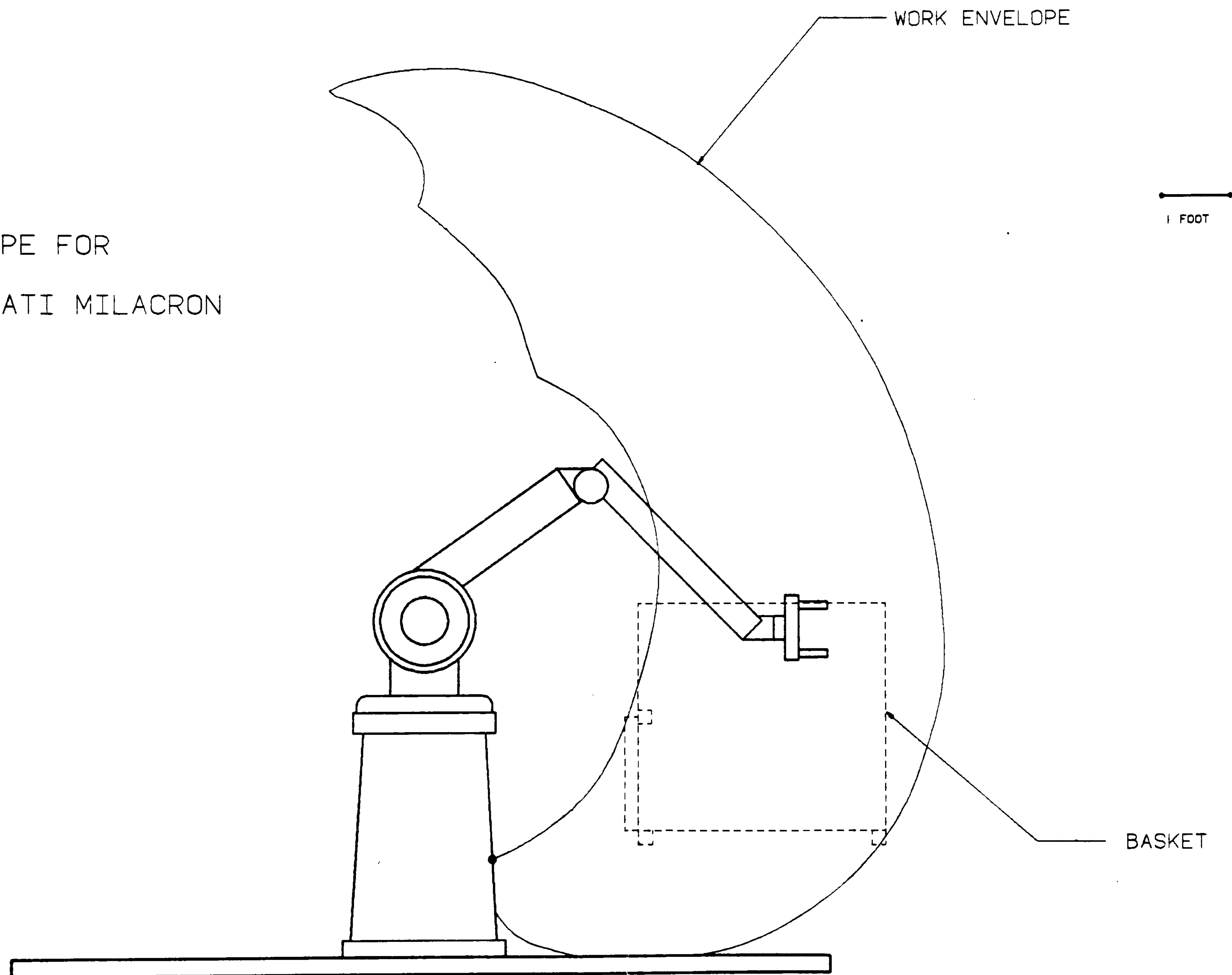


FIGURE A-4: WORK ENVELOPE FOR CINCINNATI MILACRON T3 ROBOT

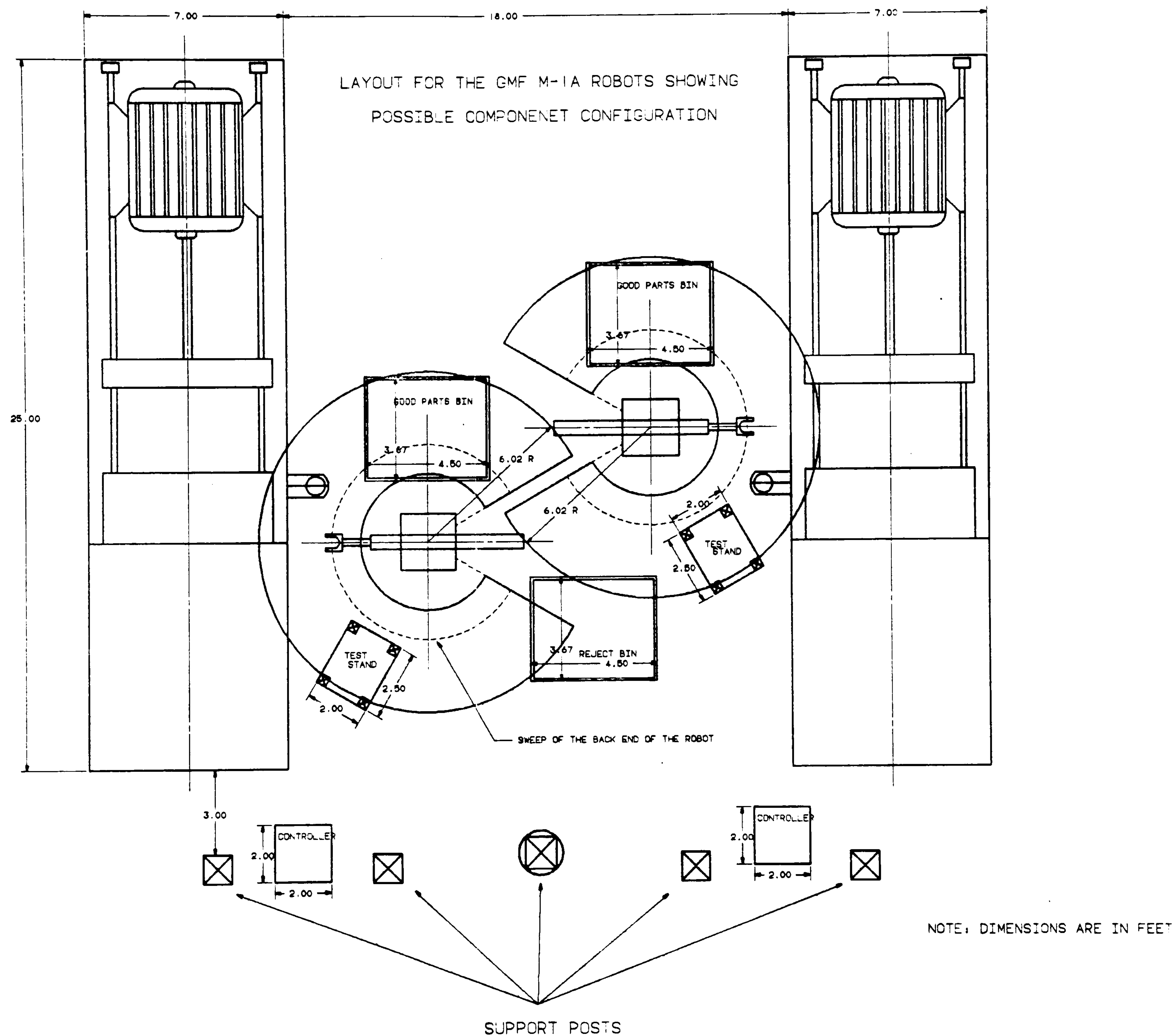


FIGURE A-5: LAYOUT FOR GMF M-1A ROBOT

# WORK ENVELOPE FOR GMF M-1A ROBOT

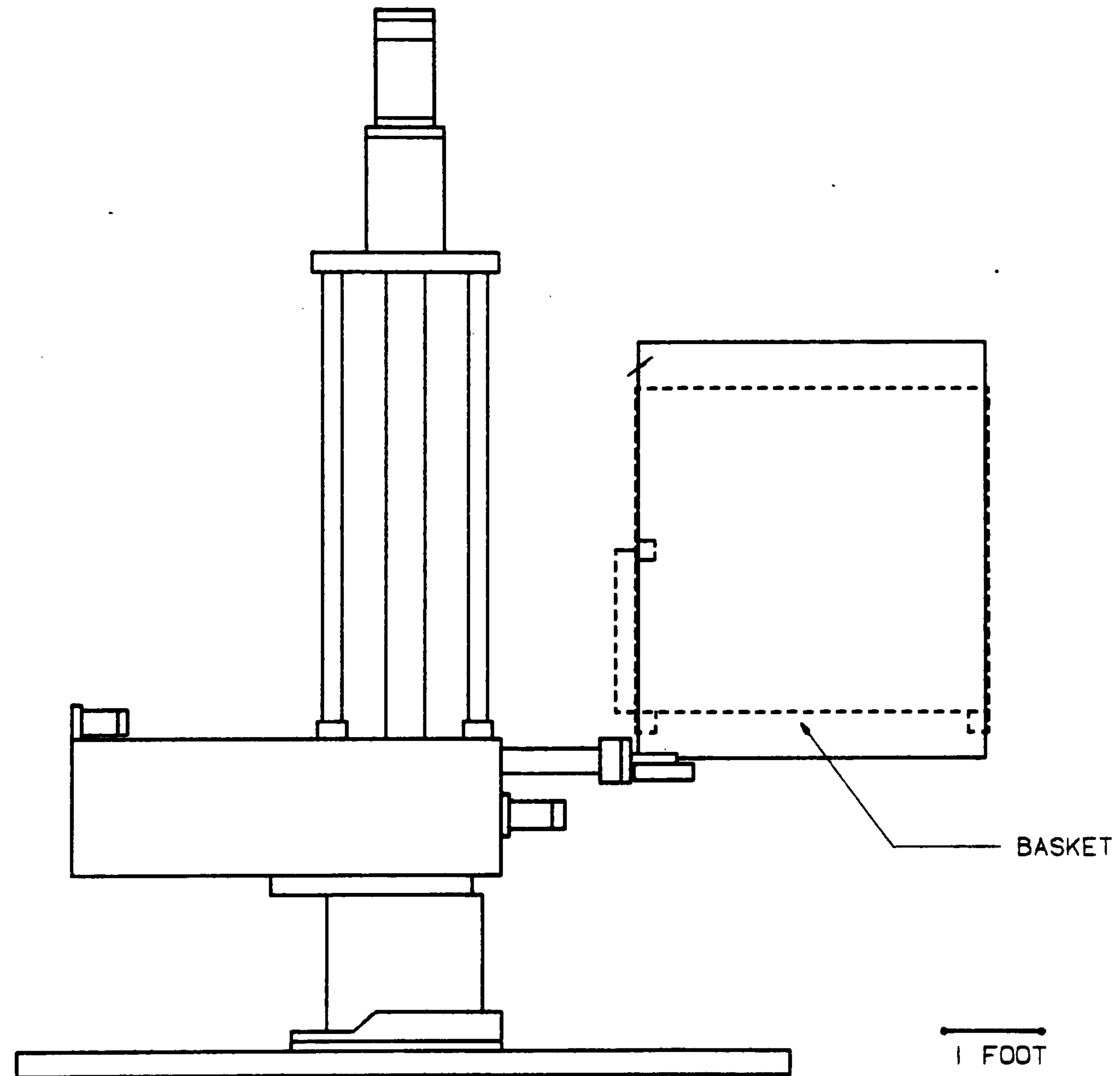
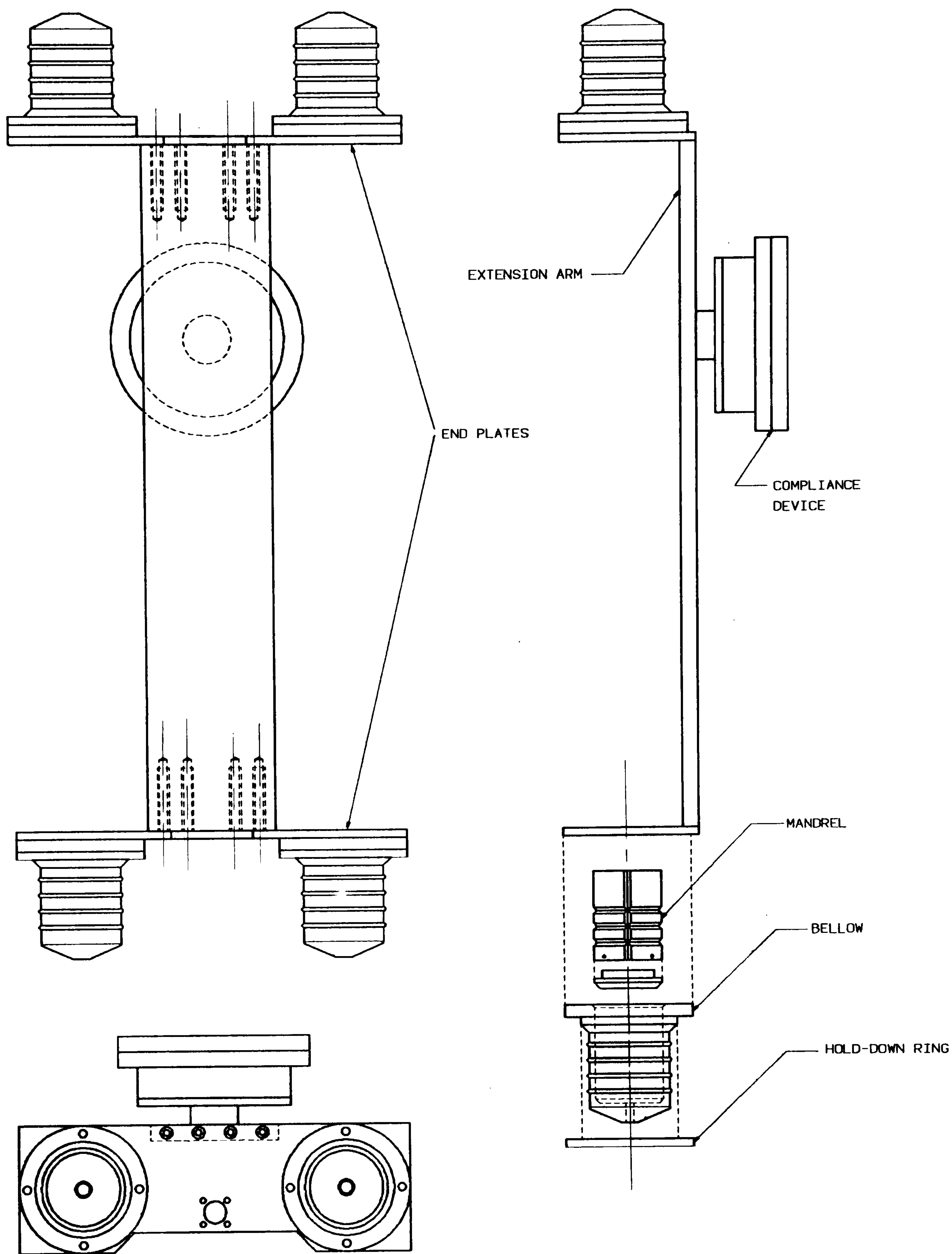


FIGURE A-6: WORK ENVELOPE FOR GMF M-1A ROBOT

FIGURE B-1



ARM EXTENSION, MAT'L : AL  
I REQUIRED

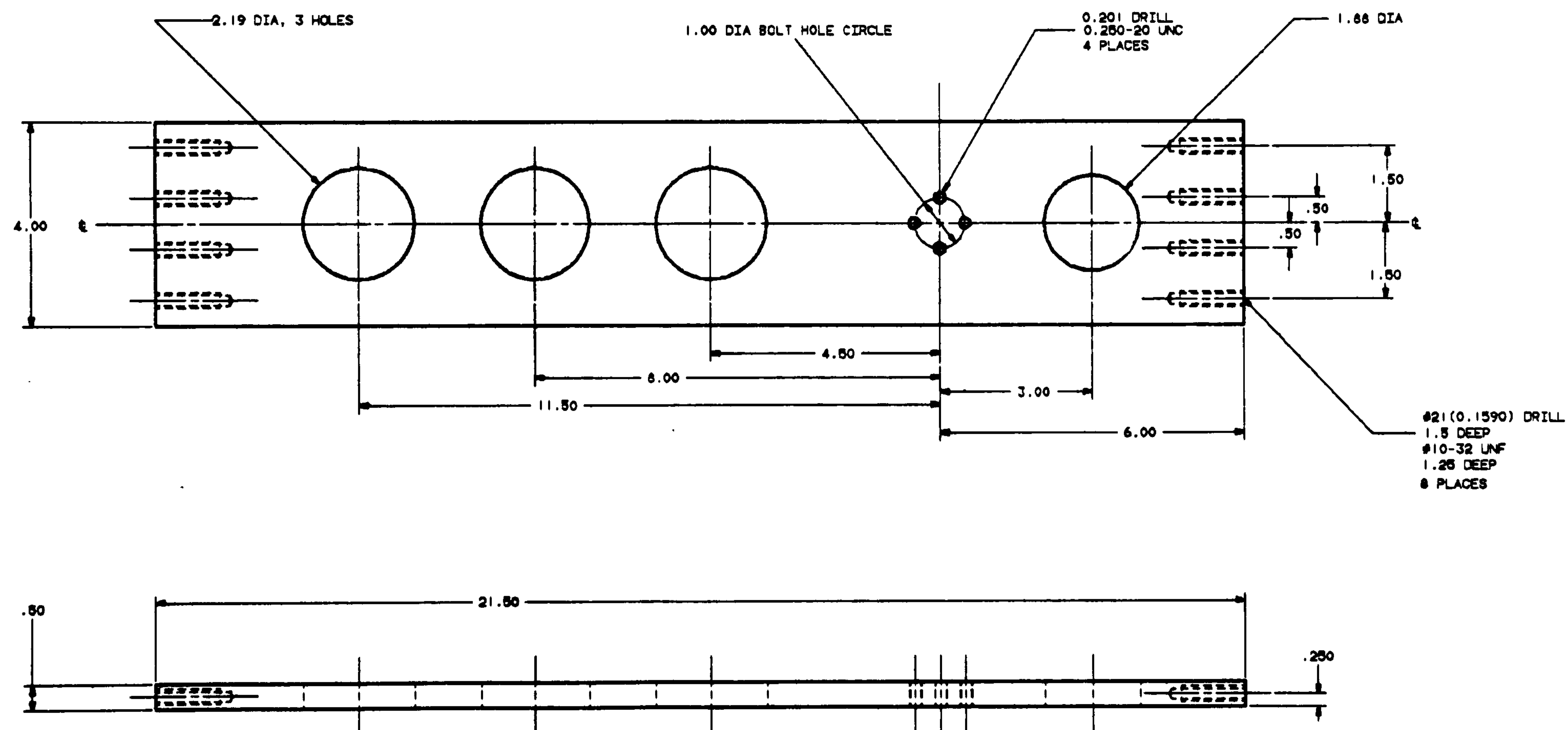


FIGURE B-2



END PLATES  
MAT'L : ALUMINUM  
2 REQUIRED

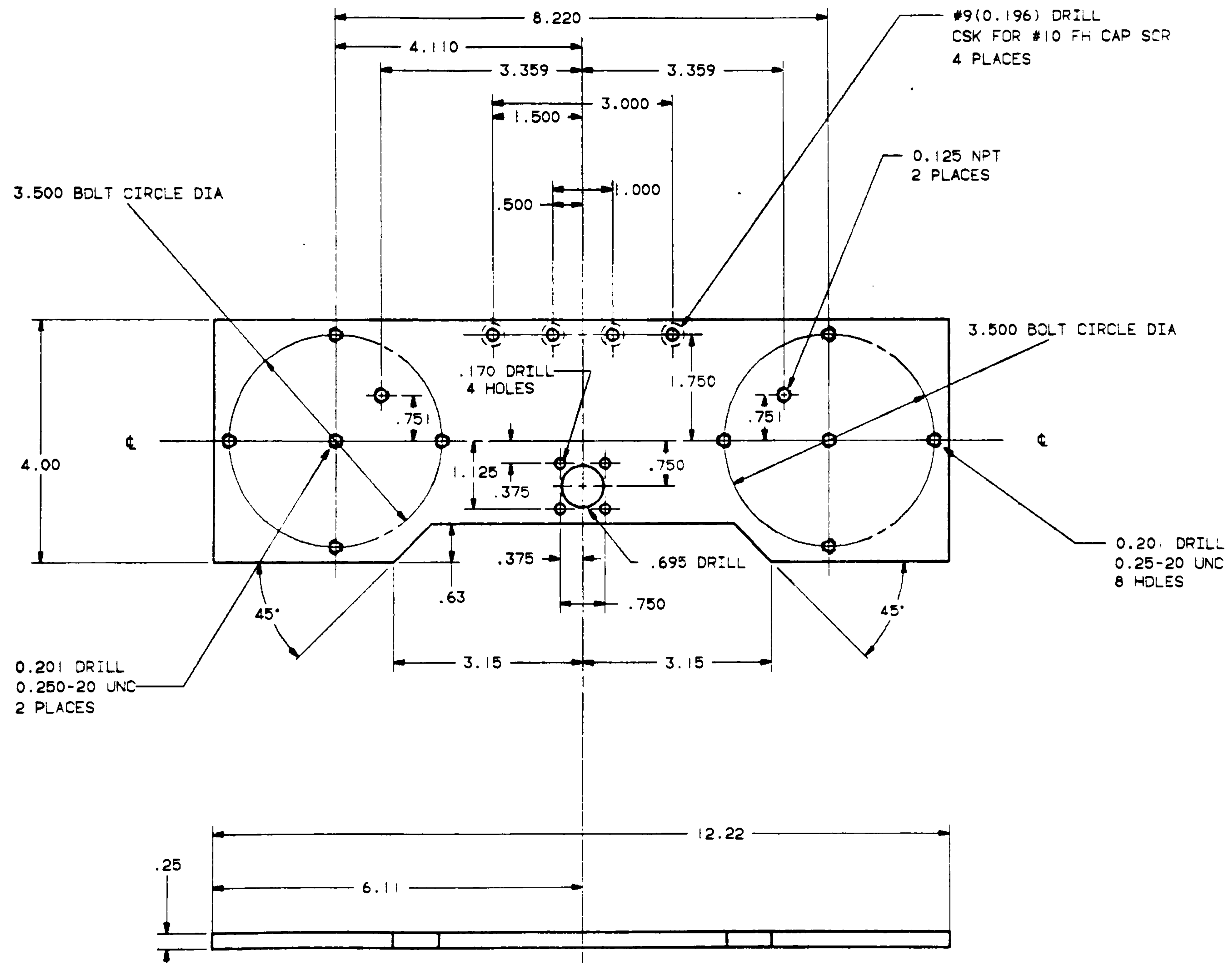


FIGURE B-3

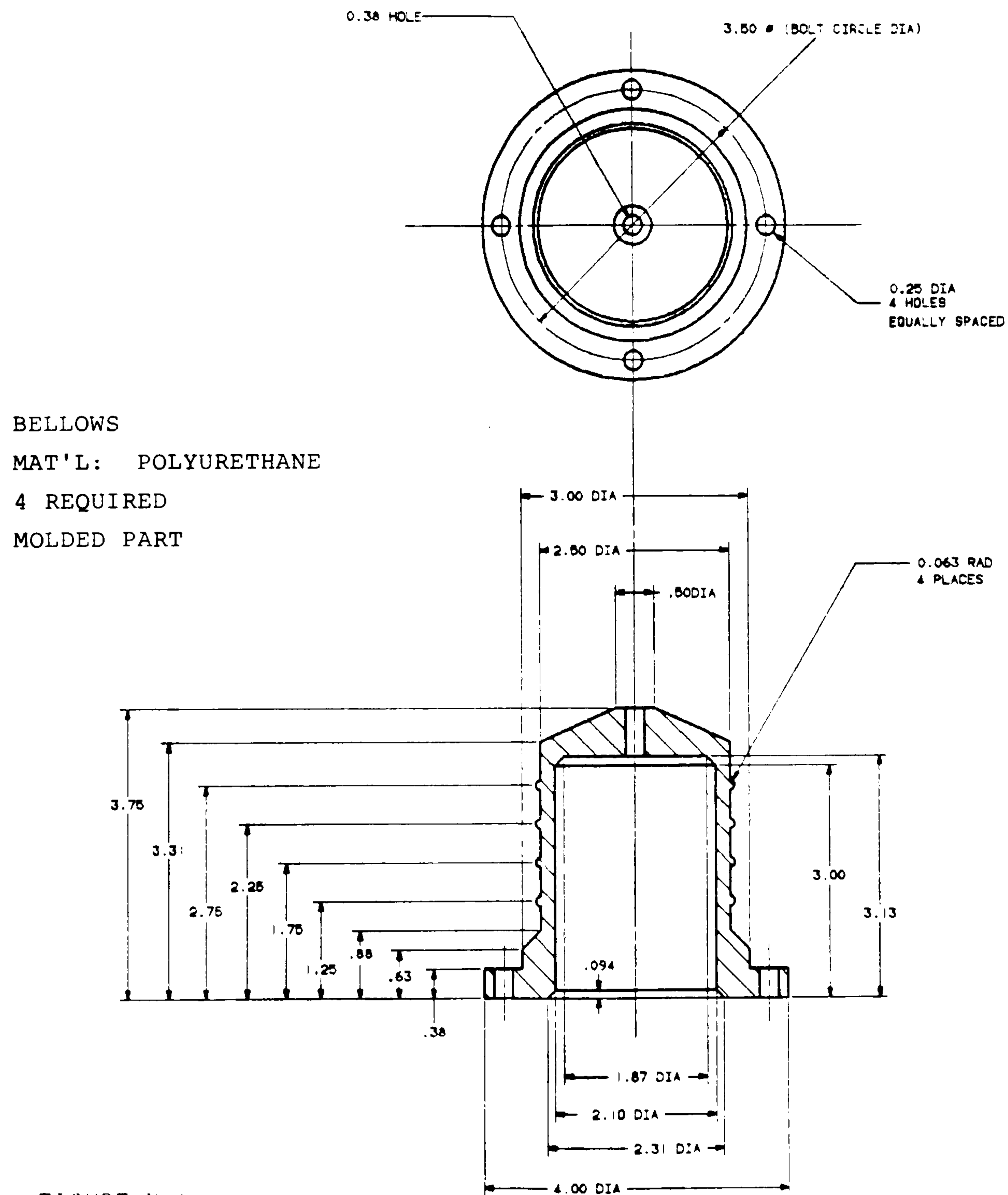
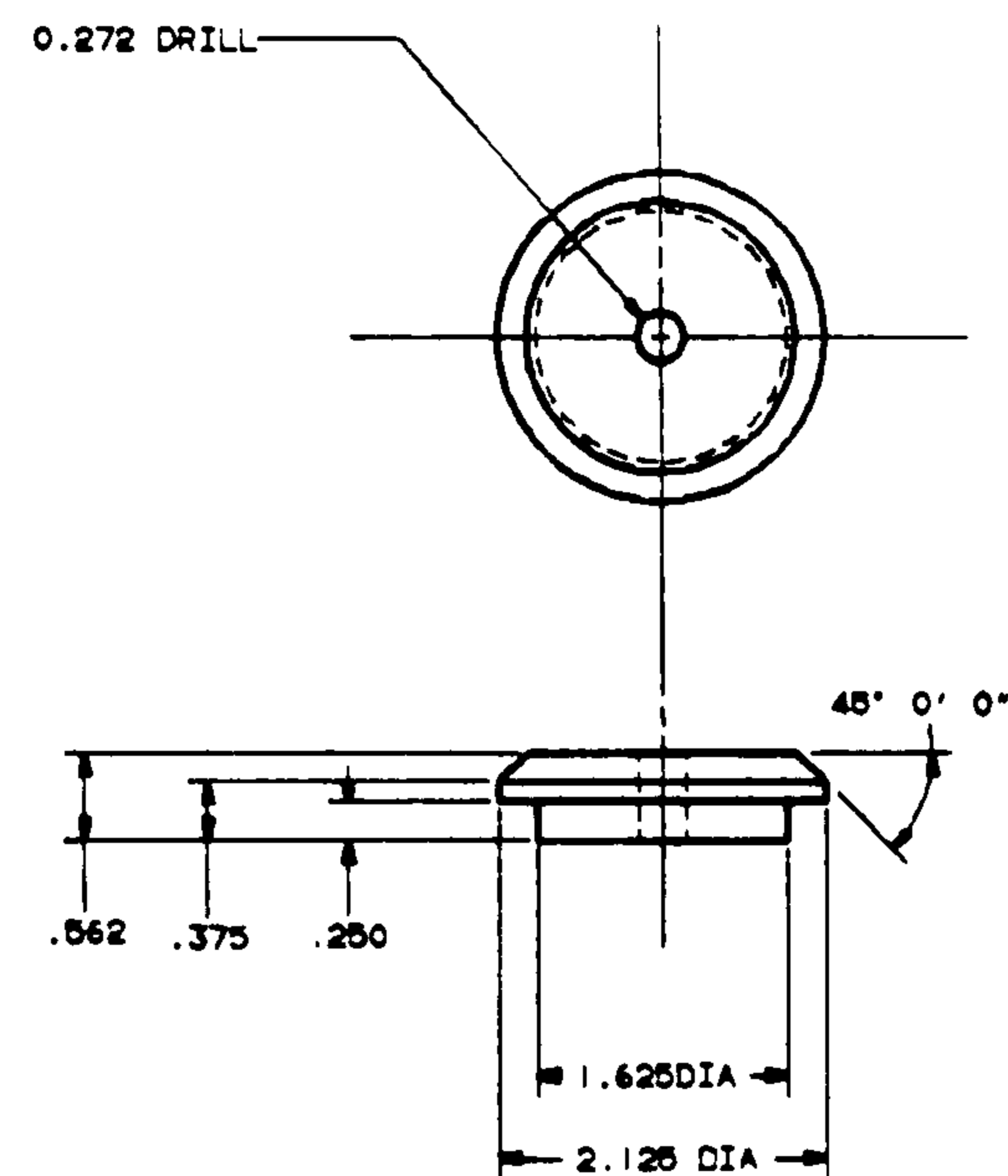
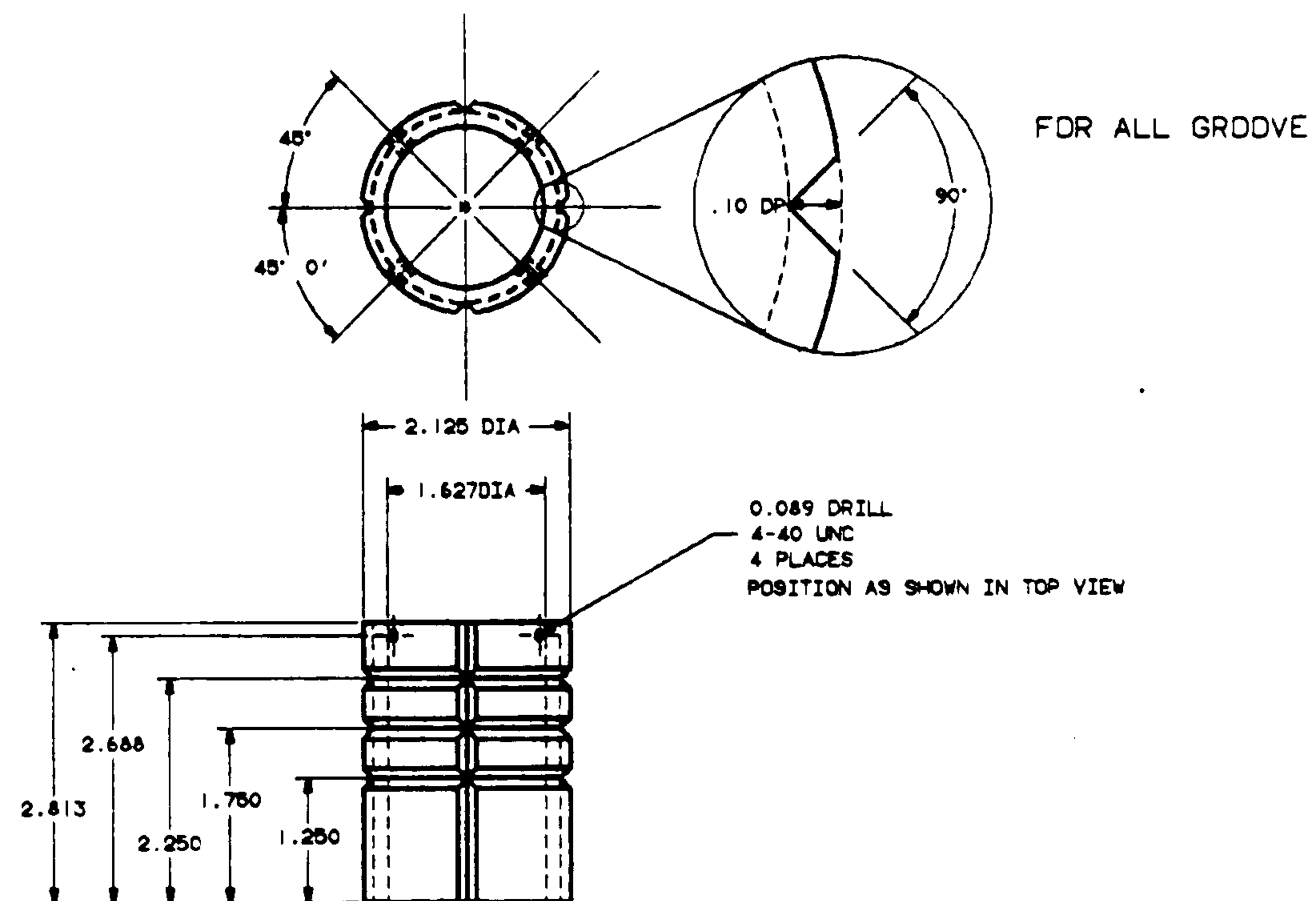


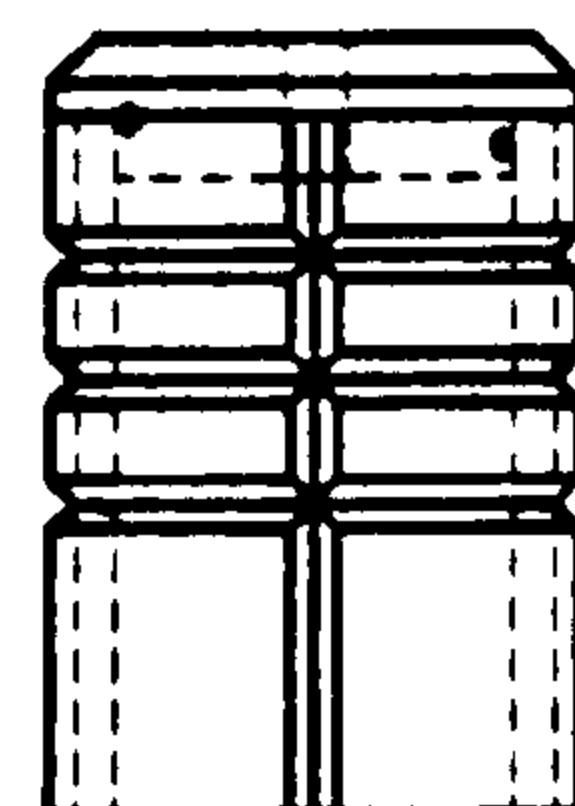
FIGURE B-4



MANDREL TOP  
MAT'L : ALUMINUM  
4 REQUIRED



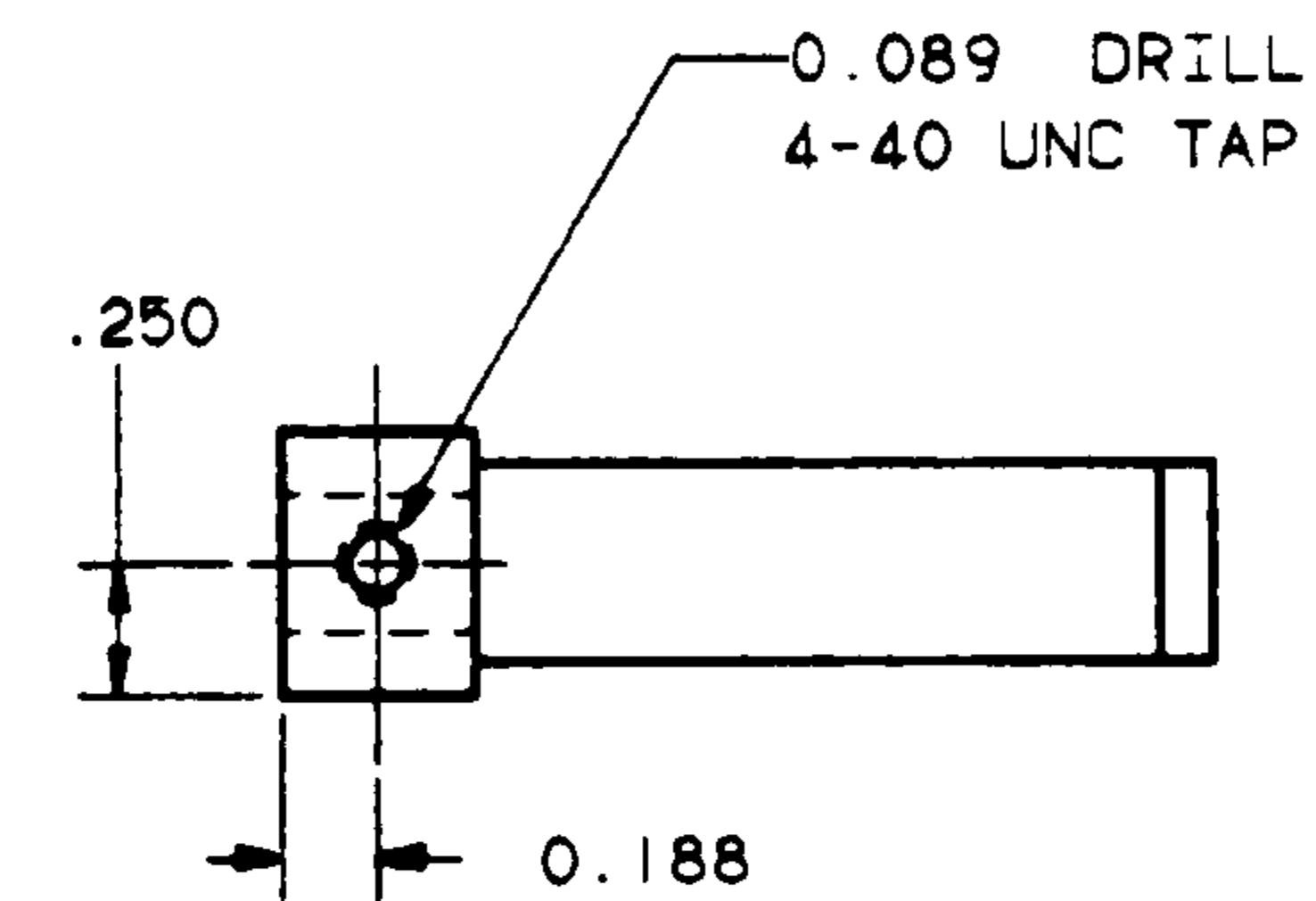
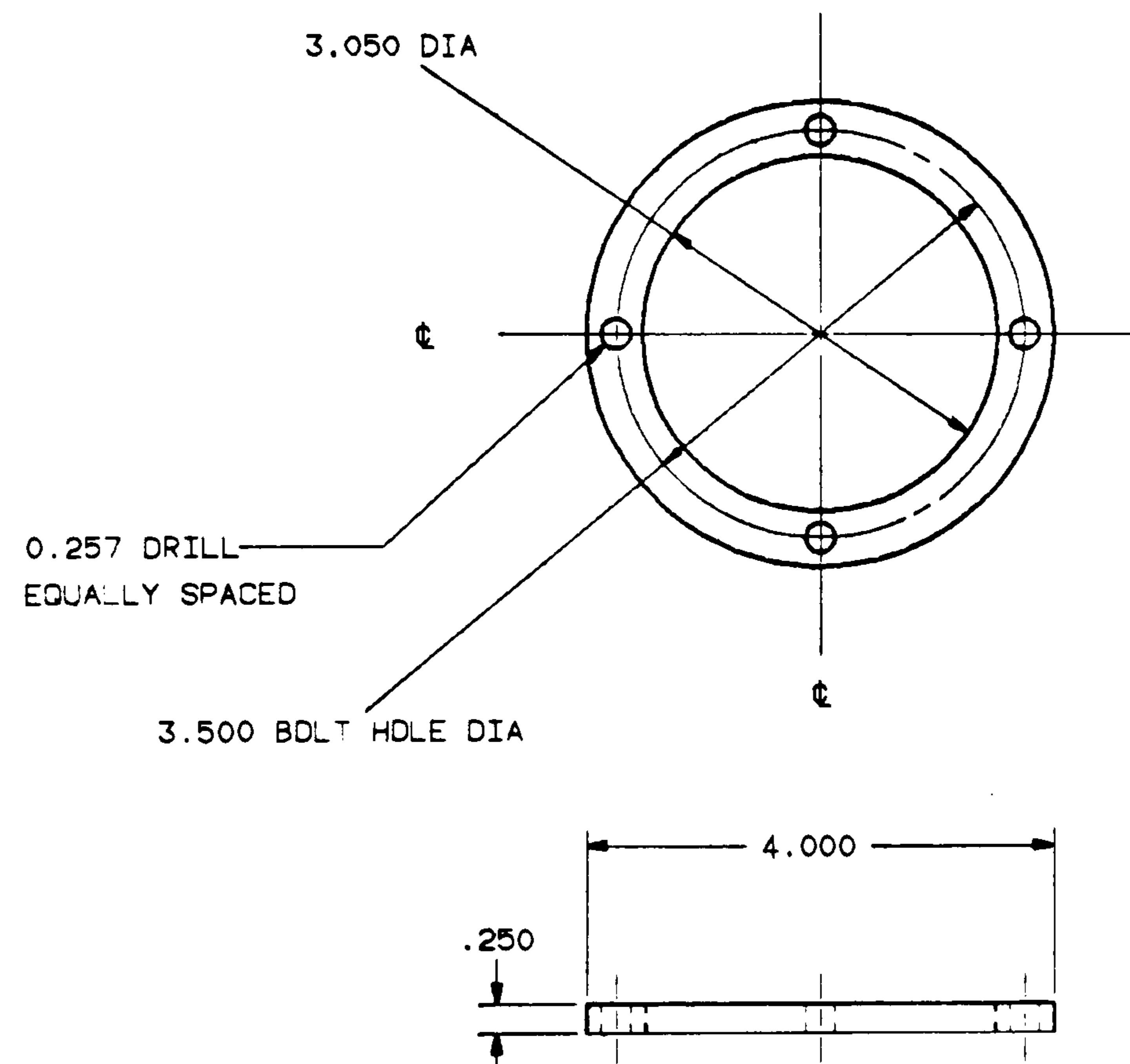
MANDREL BODY  
MAT'L : ALUMINUM  
4 REQUIRED



ASSEMBLED  
MANDREL

FIGURE B-5

HOLD DOWN PLATE  
MAT'L : ALUMINUM  
4 REQUIRED



DUNNAGE HOOK  
MAT'L : ALUMINUM  
2 REQUIRED  
2X SCALE

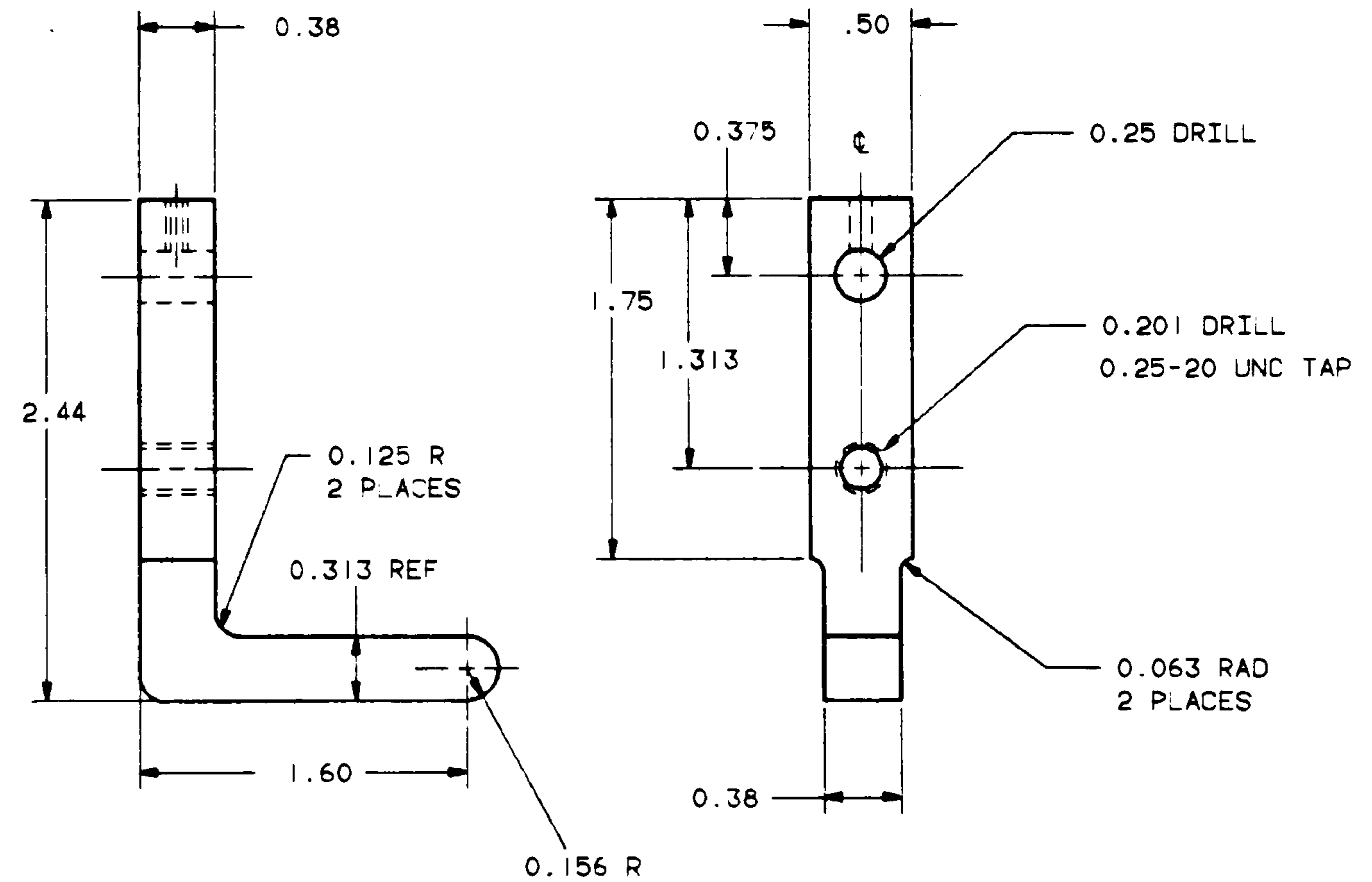
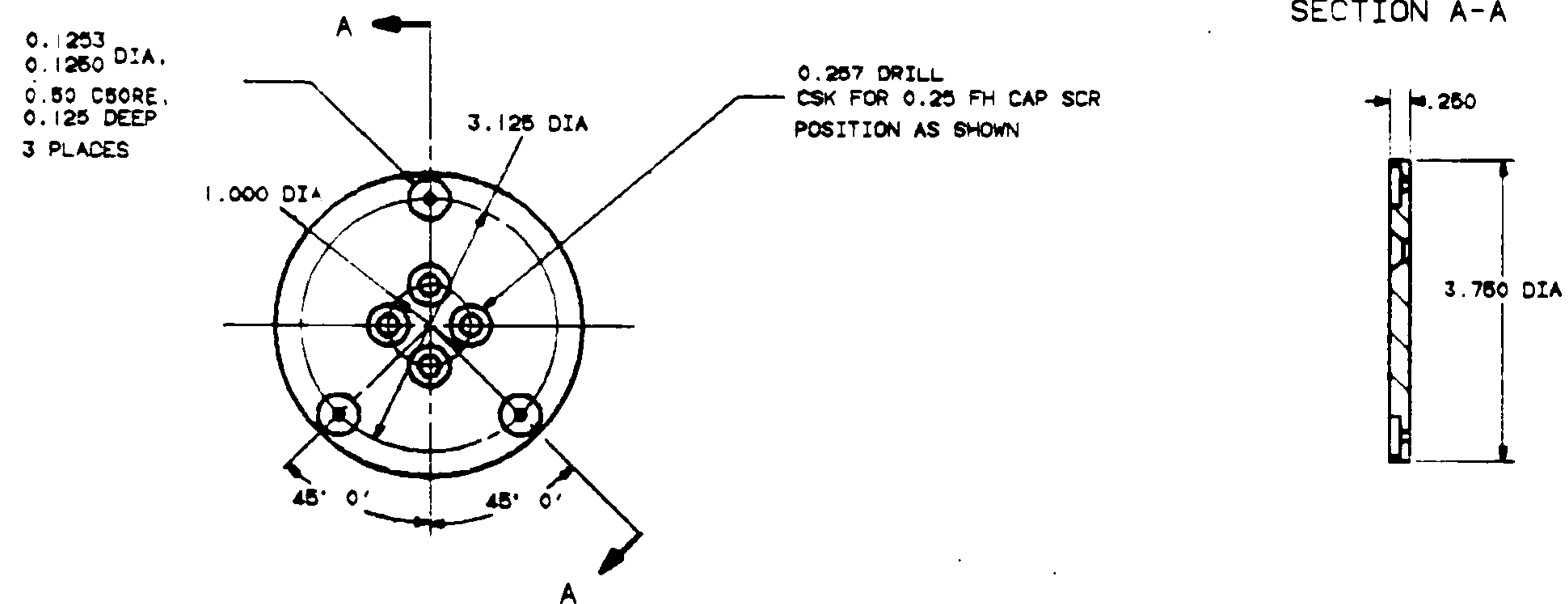
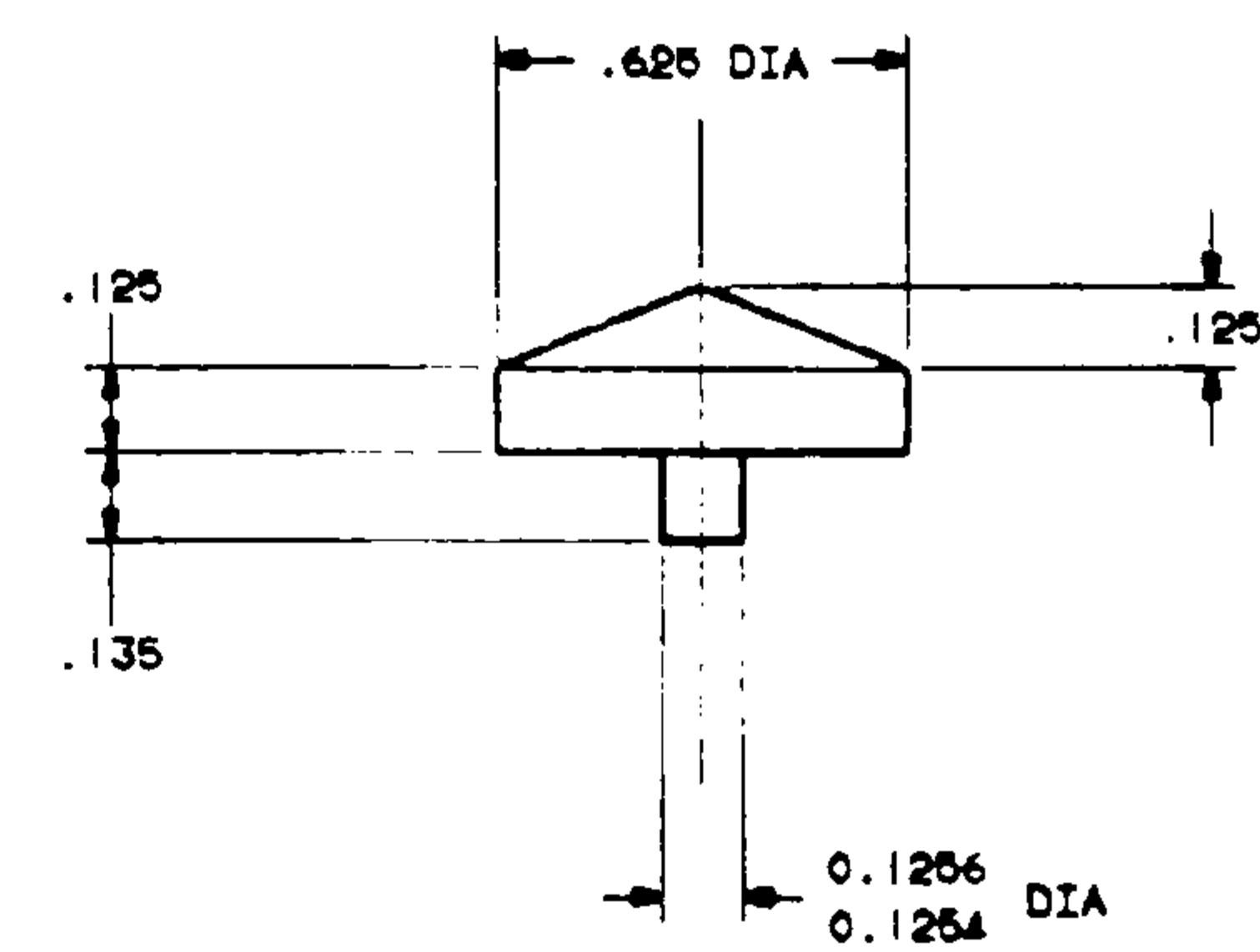
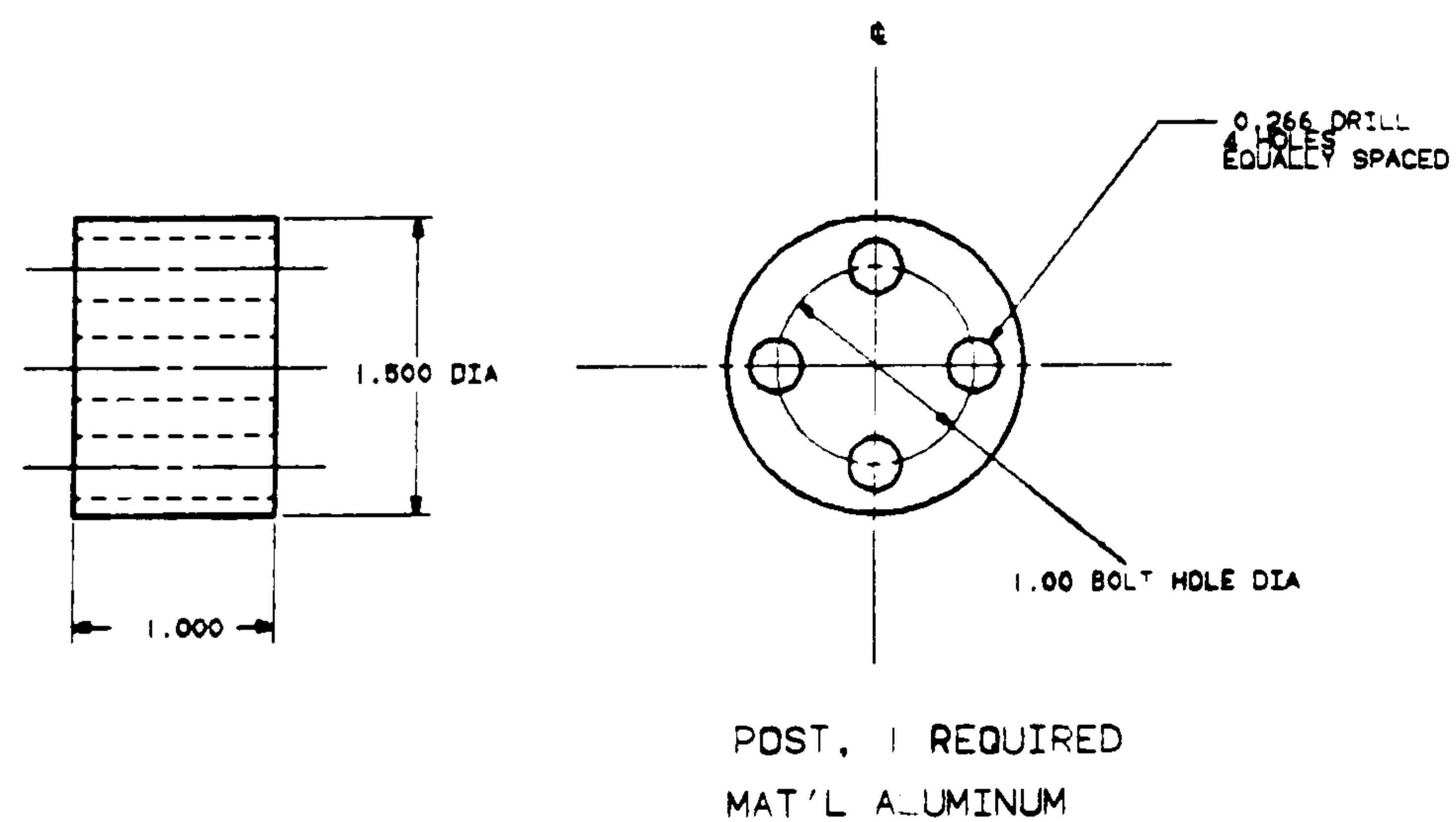
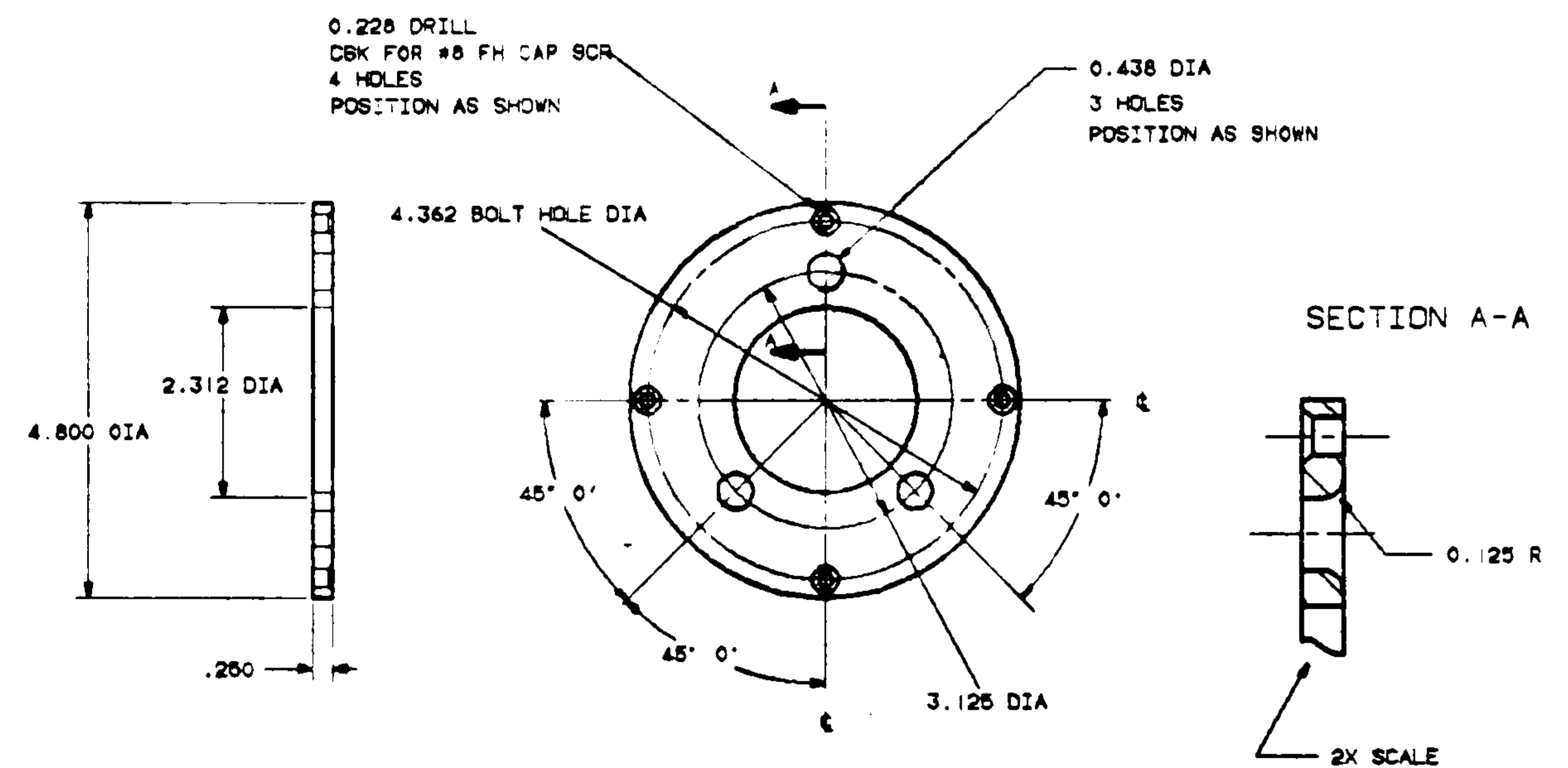


FIGURE B-6

CENTERING PLATE  
MAT'L : ALUMINUM  
1 REQUIRED

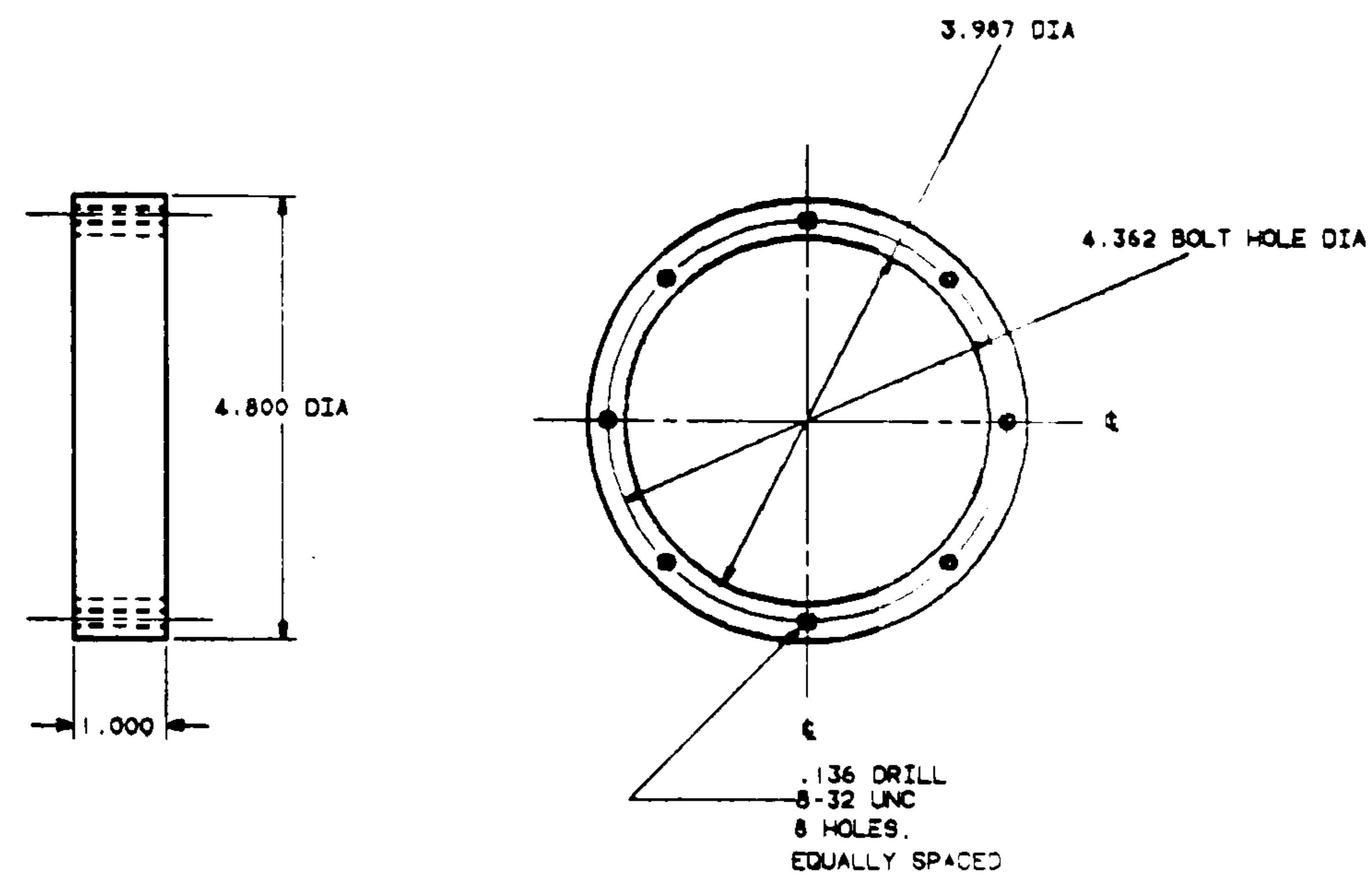


FRONT PLATE  
MAT'L : STEEL, CASE HARDEN AFTER MACHINING  
1 REQUIRED

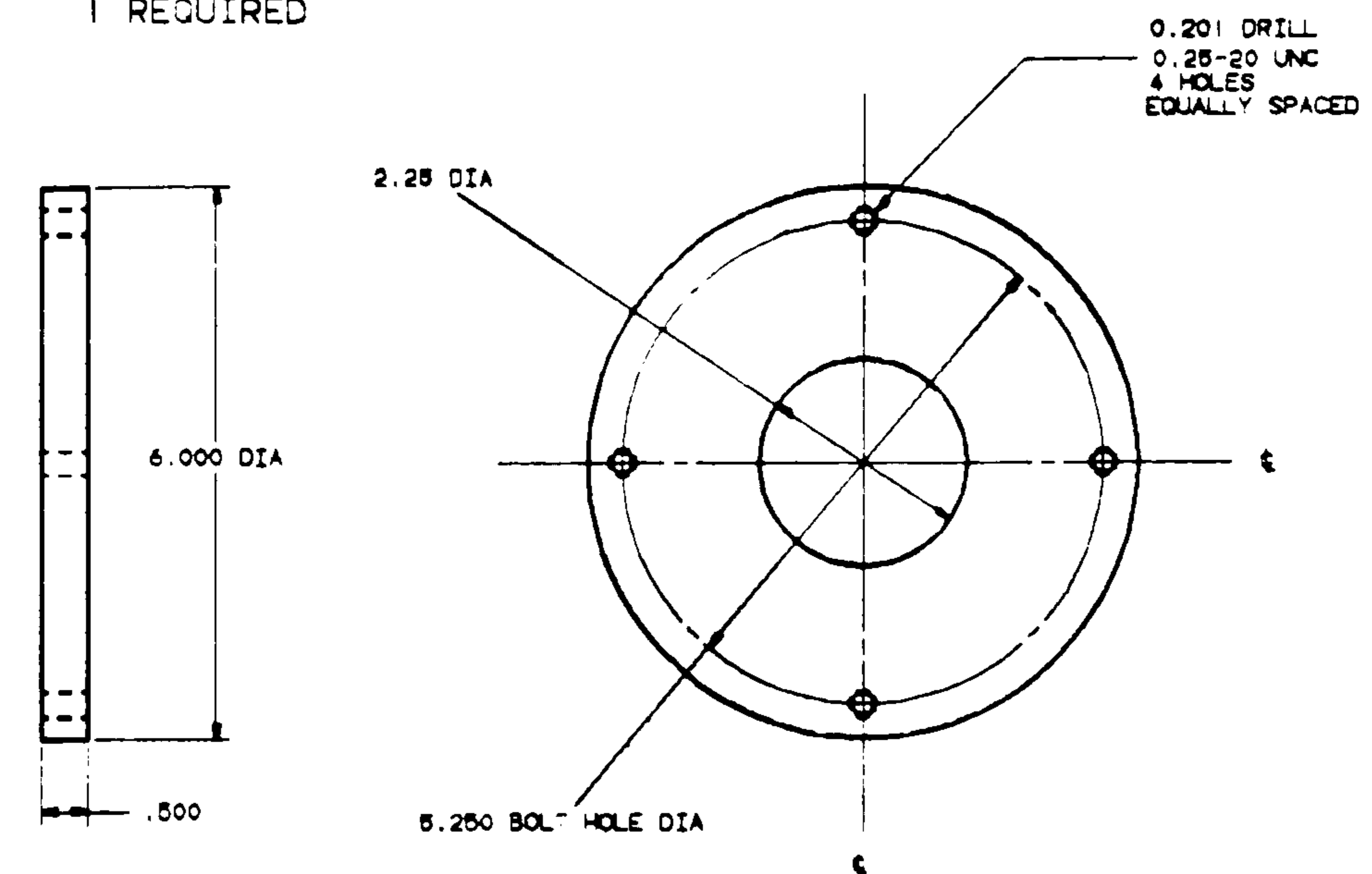


CENTERING CONE, HARDEN STEEL  
3 REQUIRED

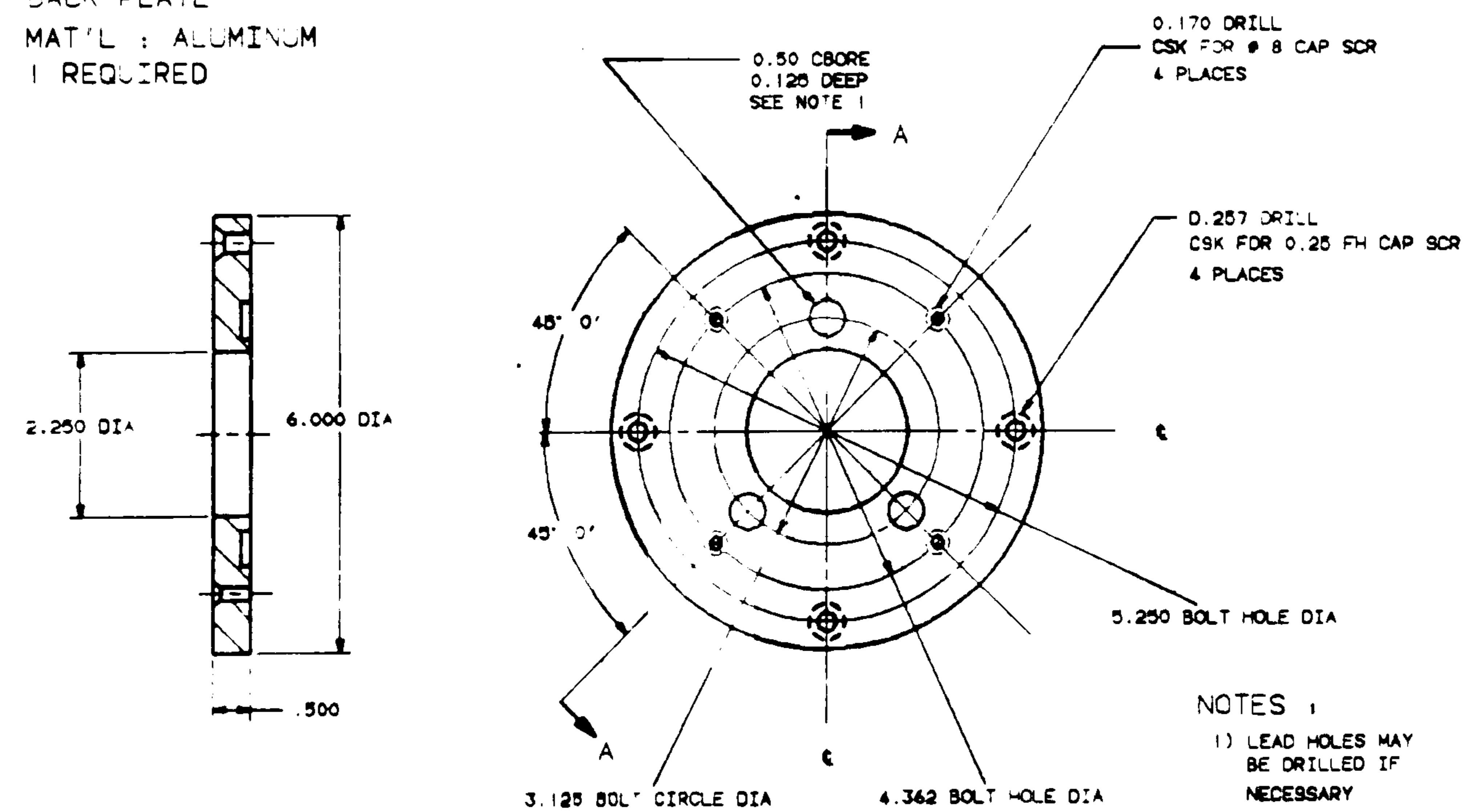
SEPERATOR RING  
MAT'L : ALUMINUM  
1 REQUIRED



ADAPTOR PLATE  
MAT'L : ALUMINUM  
1 REQUIRED



BACK PLATE  
MAT'L : ALUMINUM  
1 REQUIRED



SECTION A-A

ASSEMBLY SECTIONAL VIEW OF COMPLIANCE DEVICE

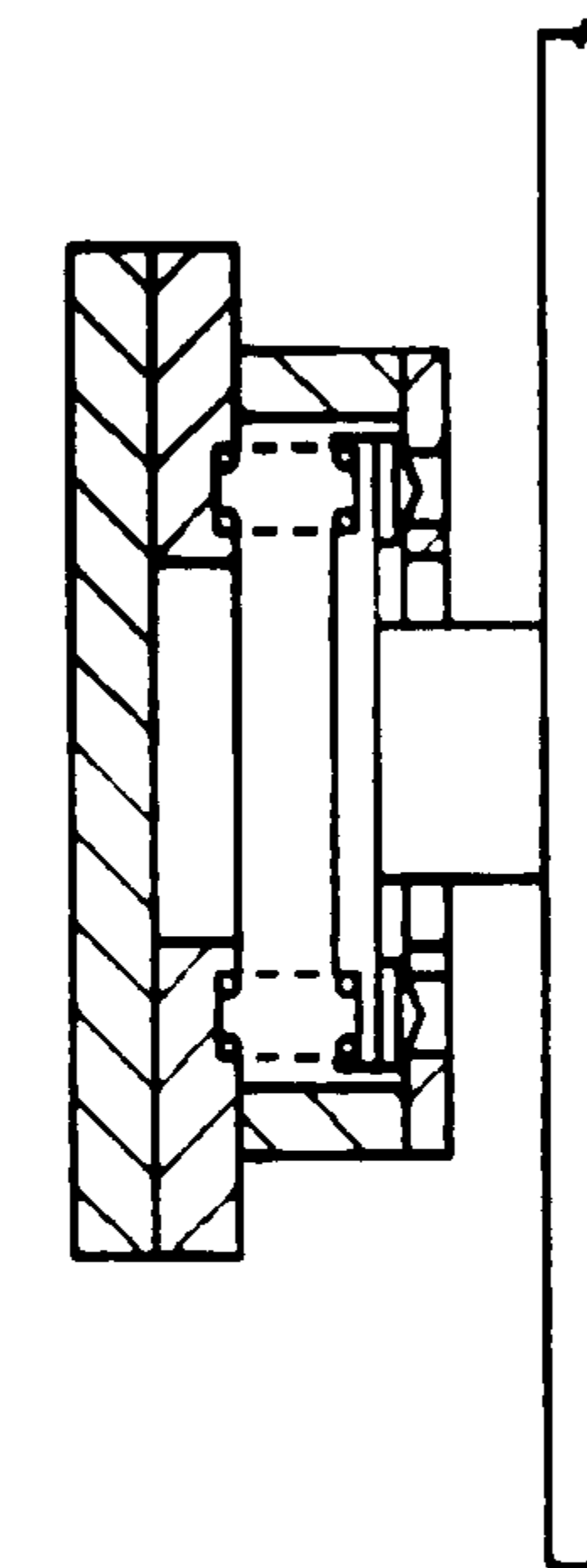
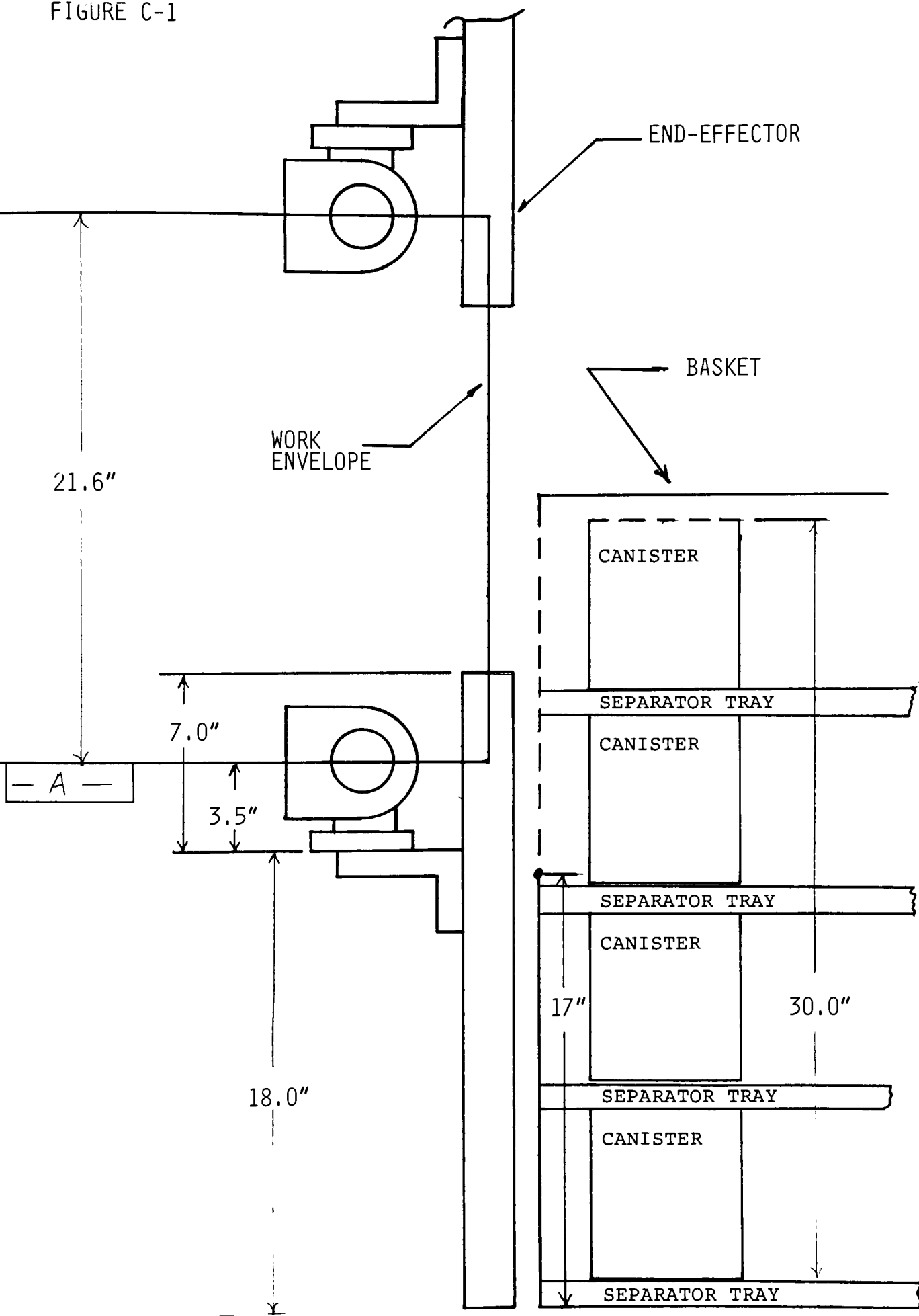


FIGURE B-6

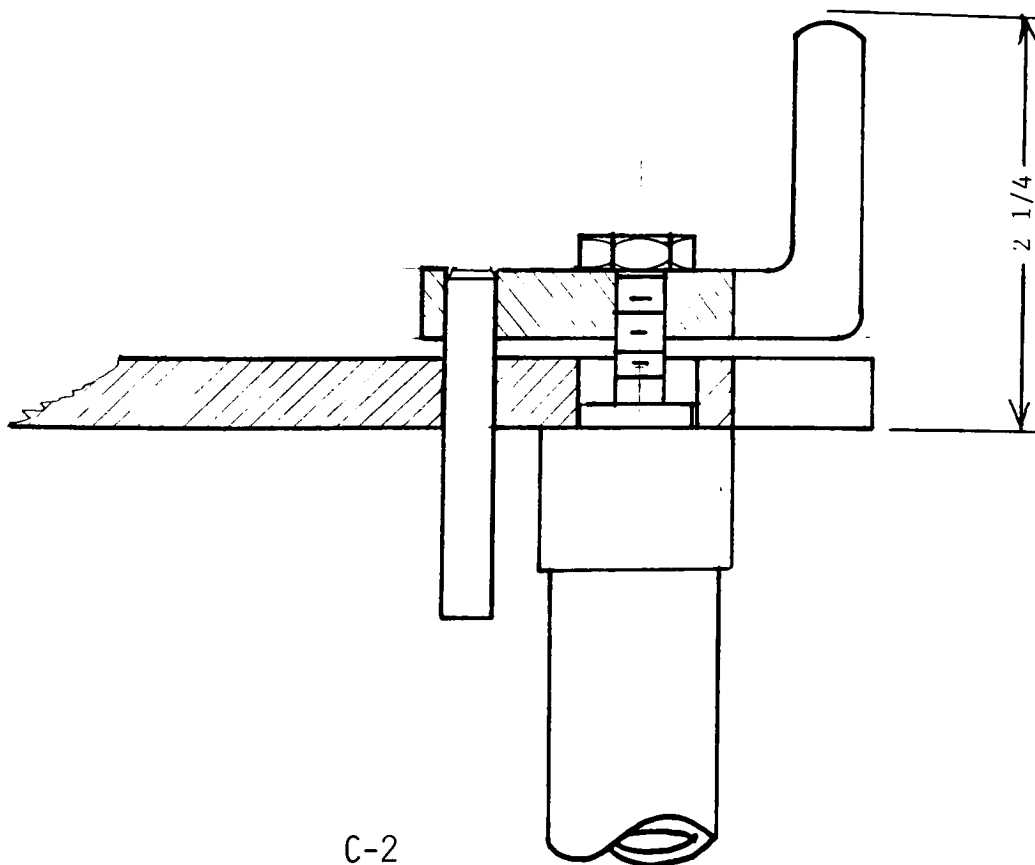
### APPENDIX C

Appendix C shows the dimensions of the end-effector in comparison to the basket, the separator tray and the canister. The dimensions for the Working Drawings were derived from this sketch.

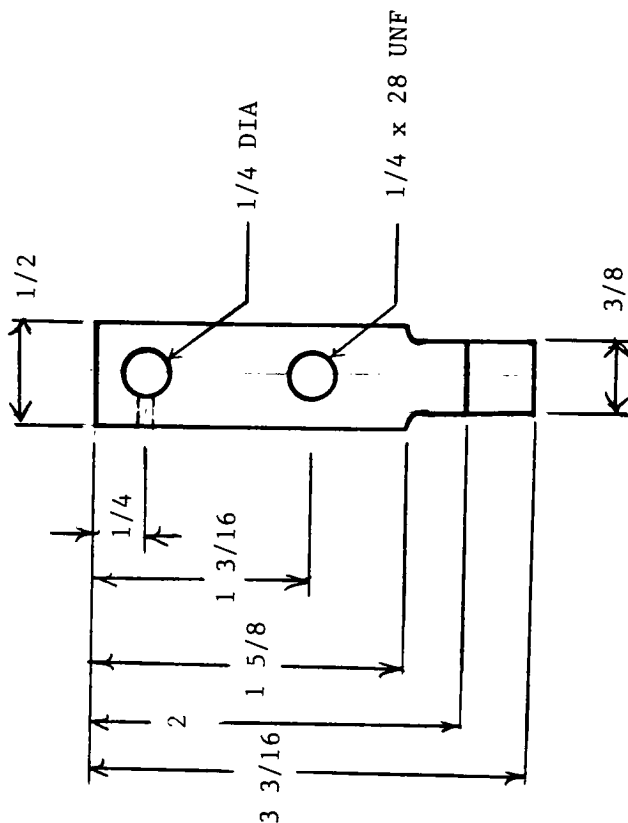
FIGURE C-1







DISTANCE BETWEEN CENTERS OF CANISTERS	:	16.40"
1/2 in. CLEARANCE ON BOTH SIDES	:	1.00"
END PLATE DISTANCE BEYOND EXTENSION ARM	:	2(2.20")
		<hr/> 21.84"

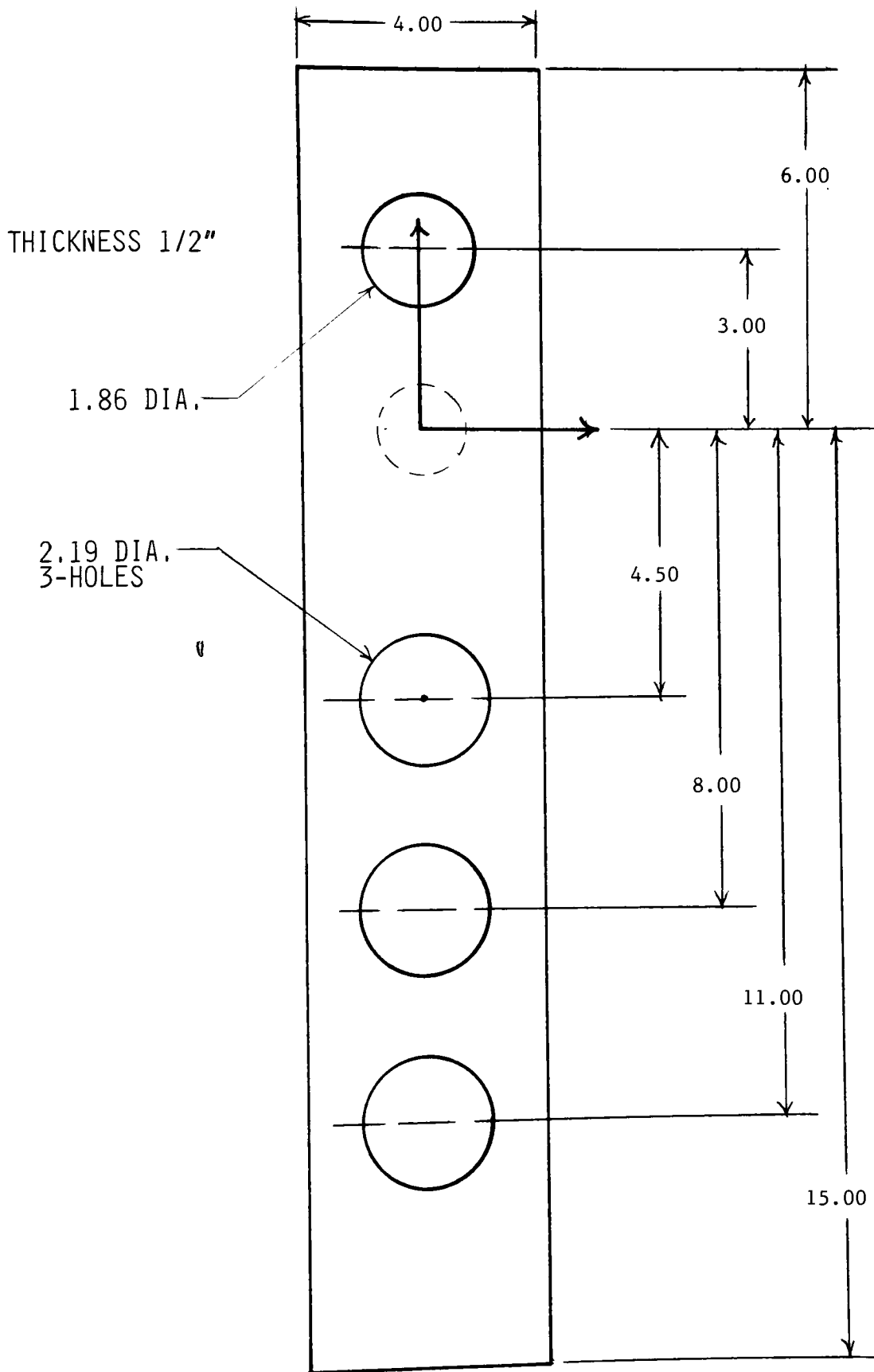


THEREFORE THE LENGTH  
OF THE EXTENSION ARM  
SHOULD BE APPROXIMATELY  
21.50"

#### APPENDIX D

This appendix contains the necessary sketches and calculations to determine the weight of the end-effector and the compliance device, and the location of the center-of-mass for the two. These values were used to determine if the robot and the robot's wrist had adequate capacity to handle the end-effector. These values were also used to determine the spring force required by the compliance device.

# EXTENSION ARM : CENTER OF MASS AND WEIGHT CALCULATIONS



$$V = [ (4.0 \text{ in})(21.5 \text{ in}) - 3\left(\frac{\pi(2.188 \text{ in})^2}{4}\right) - \left(\frac{\pi(1.875 \text{ in})^2}{4}\right) ] (0.5 \text{ in})$$

$$V = 35.98 \text{ in}^3$$

$$\rho = 0.098 \text{ lbs/in}^2$$

$$W_{\text{NET}} = 3.53 \text{ lbs}$$

### CENTER OF MASS

PART	W	$\bar{X}$	$\bar{Y}$	$W\bar{X}$	$W\bar{Y}$
1	4.21	0	-4.75	0	-20.02
2	-0.14	0	3.00	0	-0.41
3	-0.18	0	-4.50	0	+0.83
4	-0.18	0	-8.00	0	+1.47
5	<u>-0.18</u>	0	<u>-11.50</u>	0	<u>+2.12</u>
	3.52				-16.01

$$\bar{X} = 0$$

$$\bar{Y} = -4.55$$

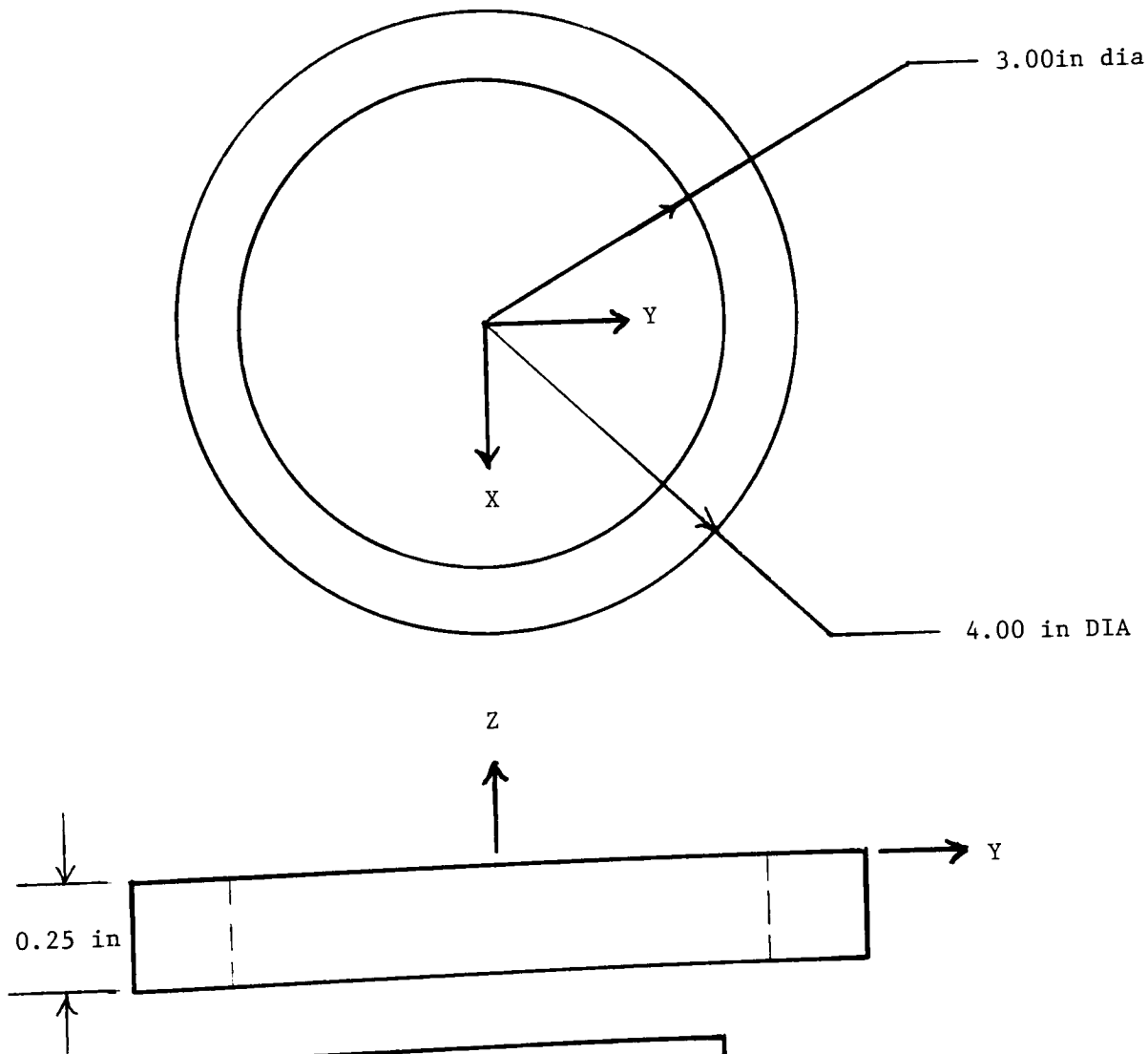
## HOLD DOWN RING

### WEIGHT

$$\begin{aligned} V &= \frac{\pi}{4} [ (4.00 \text{ in})^2 - (3.00 \text{ in})^2 ] (0.25 \text{ in}) \\ &= 1.37 \text{ in}^3 \end{aligned}$$

$$W = 0.135 \text{ lbs.}$$

$$W_{\text{NET}} = 0.540 \text{ lbs.}$$



$$\bar{X} = 0$$

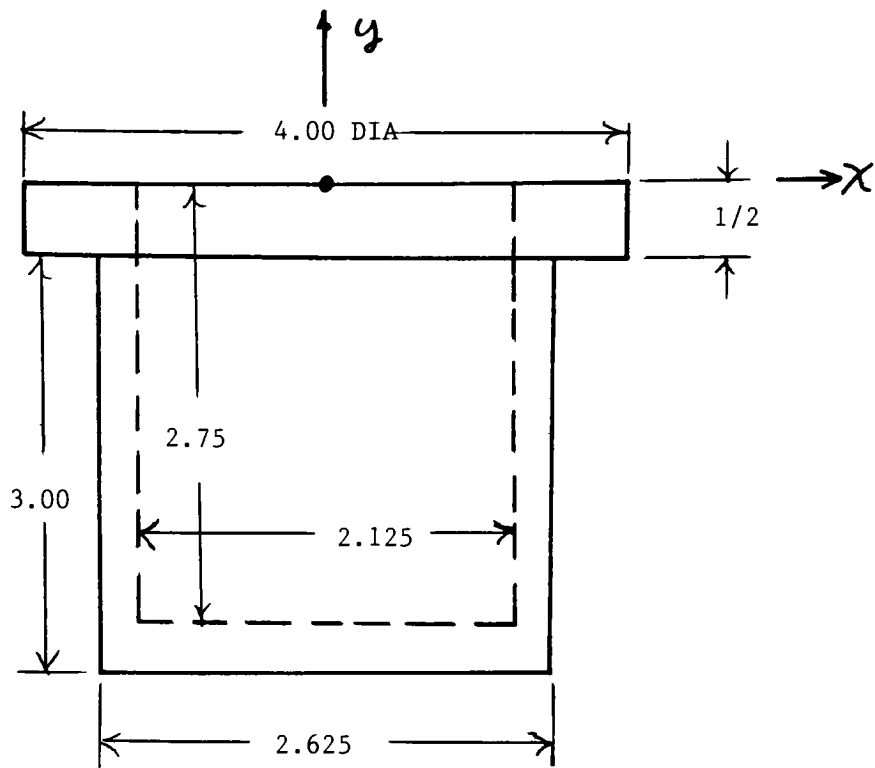
$$\bar{Y} = 0$$

$$\bar{Z} = -0.125 \text{ in.}$$

## BELLOWS

APPROXIMATE SHAPE

$$\begin{aligned}\rho &= 60 \text{ lbs./ft}^3 \\ &= 0.0347 \text{ lbs./in}^3\end{aligned}$$



## WEIGHT

$$\begin{aligned}W_1 &= \frac{\pi (2.625 \text{ in})^2}{4} (3.00 \text{ in}) (0.0347 \text{ lbs./in}^3) \\ &= 0.470 \text{ lbs}\end{aligned}$$

$$\begin{aligned}W_2 &= \frac{\pi (4.00 \text{ in.})^2}{4} (0.50 \text{ in.}) (0.0347 \text{ lbs/in}^3) \\ &= 0.218 \text{ lbs}\end{aligned}$$

$$\begin{aligned}W_3 &= - \frac{\pi (2.13 \text{ in})^2}{4} (2.75 \text{ in}) (0.0347 \text{ lbs/in}^3) \\ &= -0.338\end{aligned}$$

$$W = 0.3491 \text{ lbs}$$

$$W_{\text{NET}} = 1.40 \text{ lbs}$$

# CENTER OF MASS

PART	W	$\bar{X}$	$\bar{Y}$	$W\bar{X}$	$W\bar{Y}$
1	0.4695	0	-2.00	0	-0.9390
2	0.2180	0	-0.25	0	-0.0545
3	-0.3384	0	-1.375	0	+0.4653
<hr/>					<hr/>
0.3491					-0.5282

$$\bar{X} = 0$$

$$\bar{Y} = -1.513$$

ALUMINUM PLATE : 0.375 in thick

ALL SMALL HOLES ARE NEGLECTED FOR SAKE SIMPLICITY

$$= 0.098 \text{ lbs/in}^3$$

$$V = (4.00 \text{ in})(12.22 \text{ in})(.375 \text{ in}) - 2\left[8 \text{ in}^2 - \frac{(2.00 \text{ in})^2}{2}\right](.375 \text{ in}) \\ - [(7.50 \text{ in})(0.75 \text{ in}) - 2(0.50)(0.75 \text{ in})^2](.375 \text{ in})$$

$$V = 15.14 \text{ in}^3$$

2 END PLATES  $\Rightarrow$

$$V_{\text{NET}} = 30.3 \text{ in}^3$$

$$\text{WEIGHT} = (30.287 \text{ in}^3) * (0.098 \text{ lbs/in}^3)$$

$$W_{\text{NET}} = 2.97 \text{ lbs}$$

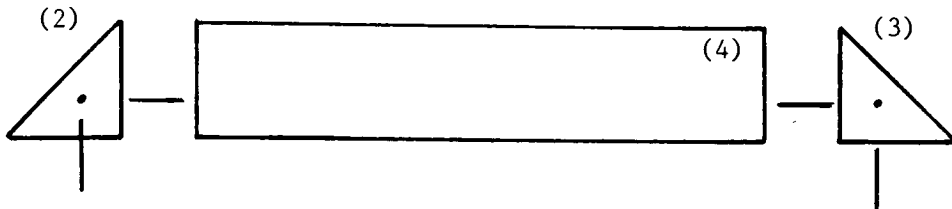
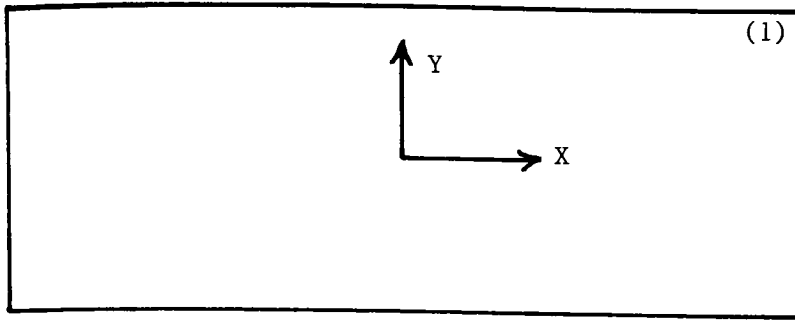
\*- NOTE: CONSIDERING THE WEIGHT DIFFERENCE BETWEEN THE TWO DESIGNS(ROUNDED vs. SQUARE) IS ONLY 0.20 lbs., WE WILL USE THE SQUARE DESIGN FOR CONSTRUCTION SIMPLICITY.

$$V_{\text{NET}} = 32.864 \text{ in}^3$$

$$W_{\text{NET}} = 3.22 \text{ lbs}$$



# CENTER OF MASS



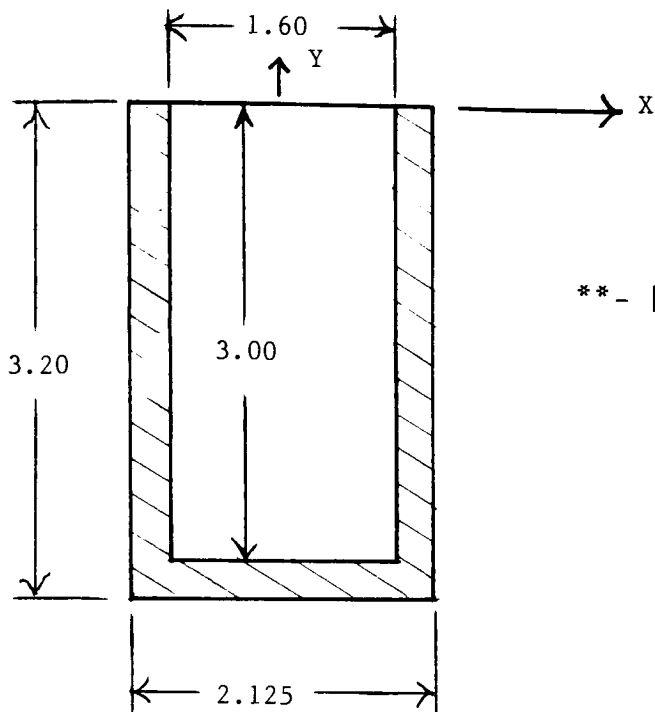
PART	W	$\bar{Y}$	$\bar{X}$	$W\bar{Y}$	$W\bar{X}$
1	1.796	0	0	0	0
2	-0.010	-2.50	-3.25	0.025	0.033
3	-0.010	-2.50	+3.25	0.025	-0.033
4	-0.165	-2.28	0	0.392	0
	<u>1.611</u>			<u>0.442</u>	<u>0</u>

$$\bar{Y} = \frac{0.442}{1.611} = 0.274 \text{ in}$$

$$\bar{X} = 0$$

$$\bar{Y} = 0.274 \text{ in}$$

# MANDRAL : WEIGHT AND CENTER OF MASS CALCULATION



\*\* - NOTE: APPROXIMATE SIZE

## WEIGHT

$$V = \frac{(2.125 \text{ in})^2}{4} (3.20 \text{ in}) - \frac{(1.60 \text{ in})^2}{4} (3.00 \text{ in})$$

$$\begin{aligned} V &= 5.32 \text{ in}^3 \\ W &= 0.52 \text{ lbs.} \\ W_{\text{NET}} &= 2.08 \text{ lbs.} \end{aligned}$$

## CENTER OF MASS

PART	W	$\bar{X}$	$\bar{Y}$	$W\bar{X}$	$W\bar{Y}$
1	1.1122	0	-1.60	0	-1.7795
2	-0.5911	0	-1.50	0	+0.8867
	<u>0.5211</u>			<u>0</u>	<u>-0.8928</u>

$$\begin{aligned} \bar{X} &= 0 \\ \bar{Y} &= -1.71 \end{aligned}$$

# PICK-UP HOOK : WEIGHT AND CENTER OF MASS CALCULATIONS

PNEUMATIC CYLINDERS APPROXIMATELY 1 lbs.  
CENTER OF MASS IS AT GEOMETRIC CENTER OF CYLINDER

MATERIAL : STEEL  $\rho = 0.286 \text{ lbs/in}^3$

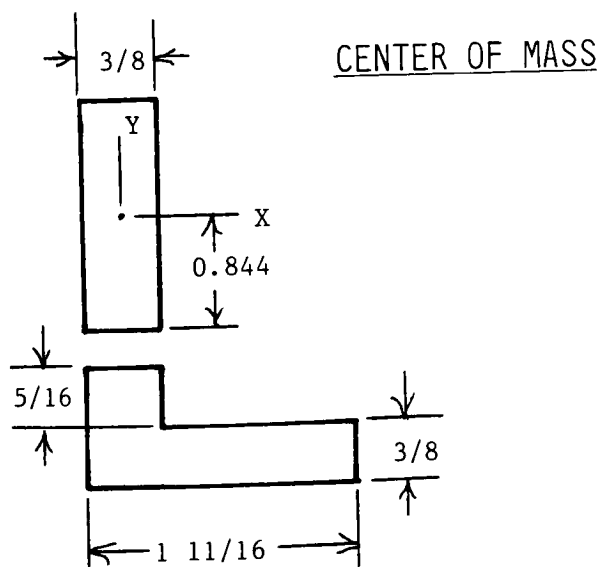
$$V = (1/2 \text{ in})(3/8 \text{ in})(1 \frac{11}{16} \text{ in}) - 2\left[\frac{\pi (1/4 \text{ in})^2}{4}\right] (3/8 \text{ in})$$

$$+ [(1 \frac{5}{8} \text{ in})(3/8 \text{ in}) + (5/16 \text{ in})(3/8 \text{ in})](3/8 \text{ in})$$

$$V = 0.55 \text{ in}^3$$

WEIGHT  $W_{\text{NET}} = 0.32 \text{ lbs.}$

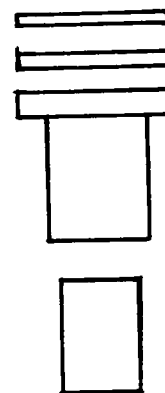
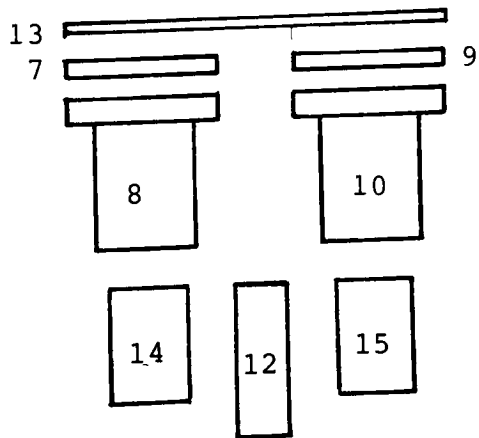
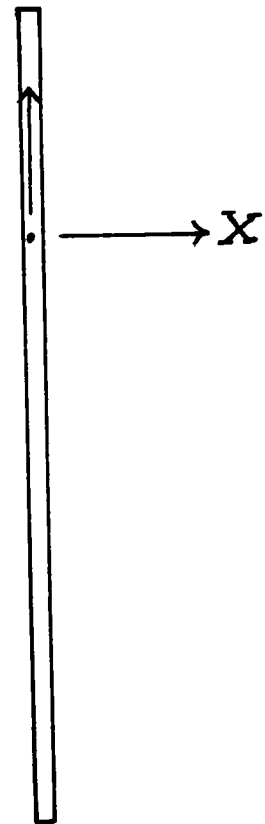
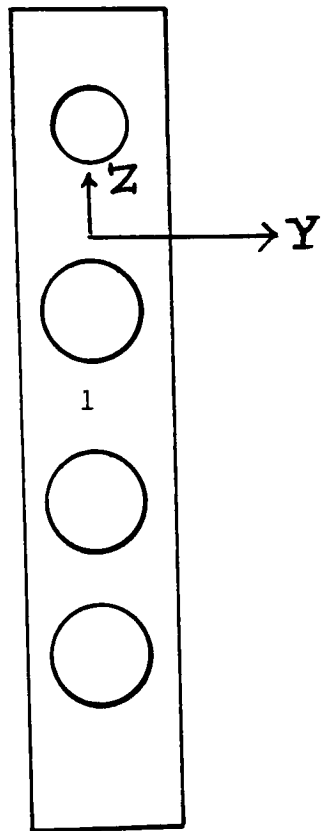
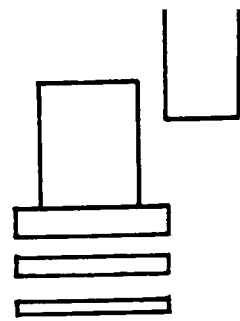
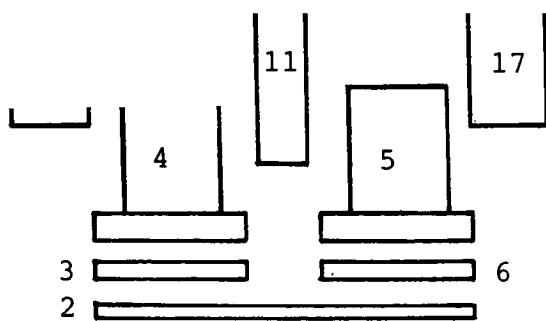
2 PARTS



$$\bar{X} = 0.410$$

$$\bar{Y} = -0.607$$

	W	$\bar{X}$	$\bar{Y}$	$W\bar{X}$	$W\bar{Y}$
1	0.091	0	0	0	0
2	0.013	0	-1	0	-0.013
3	0.068	1.0313	-1.34	0.070	-0.092
	<u>0.171</u>			<u>0.070</u>	<u>-0.104</u>



TOTAL WEIGHT OF THE END-EFFECTOR

$W_1 = 3.530$   
 $W_2 = 1.610$   
 $W_3 = 0.135$   
 $W_4 = 0.350$   
 $W_5 = 0.350$   
 $W_6 = 0.135$   
 $W_7 = 0.135$   
 $W_8 = 0.350$   
 $W_9 = 0.135$   
 $W_{10} = 0.350$   
 $W_{11} = 1.160$   
 $W_{12} = 1.160$   
 $W_{13} = 1.160$   
 $W_{14} = 0.520$   
 $W_{15} = 0.520$   
 $W_{16} = 0.520$   
 $W_{17} = 0.520$

---

---

$W_{NET} = 13.1 \text{ lbs.}$

END-EFFECTOR'S CENTER-OF-MASS

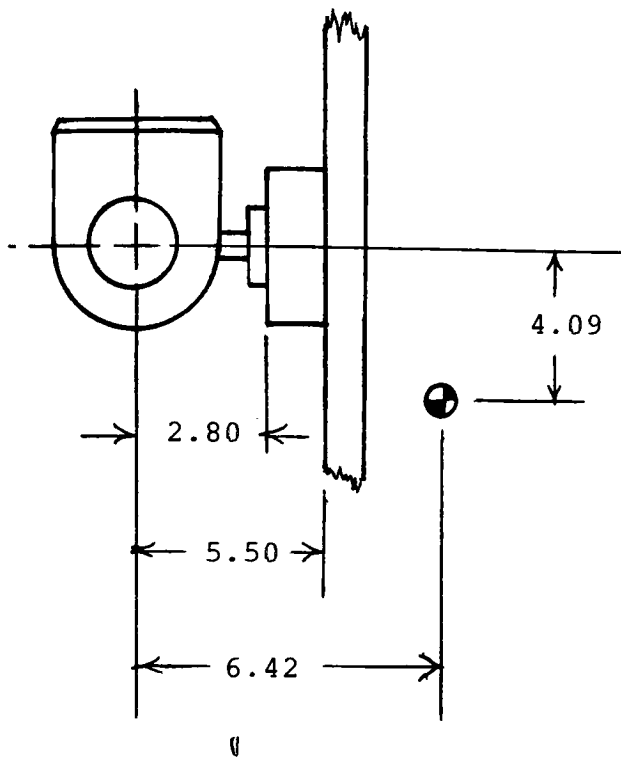
PART	W	X	Y	Z	W <sub>x</sub>	W <sub>y</sub>	W <sub>z</sub>
1	3.530	0.0	0.0	-4.550	0.0	0.0	-8.080
2	1.610	1.476	0.0	6.188	2.376	0.0	9.962
3	0.135	1.750	-4.110	6.813	0.236	-0.555	0.920
4	0.350	1.750	-4.110	7.888	0.613	-1.439	2.758
5	0.350	1.750	4.110	7.888	0.613	1.439	2.758
6	0.135	1.750	4.110	6.813	0.236	0.555	0.920
7	0.135	1.750	-4.110	-16.313	0.263	-0.555	-2.202
8	0.350	1.750	-4.110	-17.388	0.613	-1.439	-6.086
9	0.135	1.750	4.110	-16.313	0.236	0.555	-2.202
10	0.350	1.750	4.110	-17.388	0.613	1.439	-6.086
11	1.160	2.625	0.0	8.000	3.045	0.0	9.280
12	1.160	2.625	0.0	-17.500	3.045	0.0	-20.300
13	1.610	1.476	0.0	-15.688	2.376	0.0	-25.257
14	0.520	1.750	-4.110	-17.585	0.910	0.0	-9.144
15	0.520	1.750	4.110	-17.585	0.910	2.137	-9.144
16	0.520	1.750	-4.110	8.085	0.910	-2.137	4.204
17	0.520	1.750	4.110	8.085	0.910	2.137	4.204
<hr/> <hr/>					<hr/> <hr/>	<hr/> <hr/>	<hr/> <hr/>
13.09					17.878	0.0	-53.496

X = 1.37 in.

Y = 0.0

Z = -4.09 in

## MOMENT EXERTED ON THE ROBOT'S WRIST



NET MOMENT EXERTED BY THE END-EFFECTOR ONTO THE  
F2 WRIST :

$$M = (6.42\text{in.})13.09 \text{ lbs.}$$

$$M = 7.0 \text{ Ft-lbs}$$

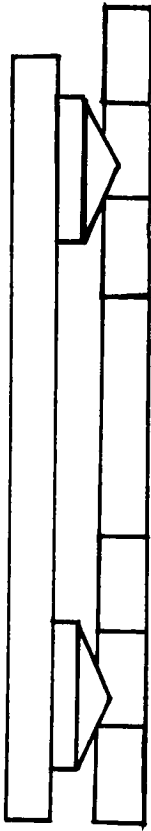
## APPENDIX E

This appendix contains the calculations necessary to determine the required spring force needed to keep the compliance device in place while the robot is moving it. Three modes of displacement were considered. These were slippage, lifting, and rotation(see FIGURE E-1). Since modes I and III are similar only modes II and III were considered. The maximum dynamic loading situation occurs when the end-effector's center of mass is below the compliance device's centerline, the robot's arm is fully extended and it is rotating about the Z-axis at the maximum angular velocity. The minimum spring force required to keep the compliance device stationary while undergoing maximum dynamic loading is 120 lbs. per spring (see page E-7).

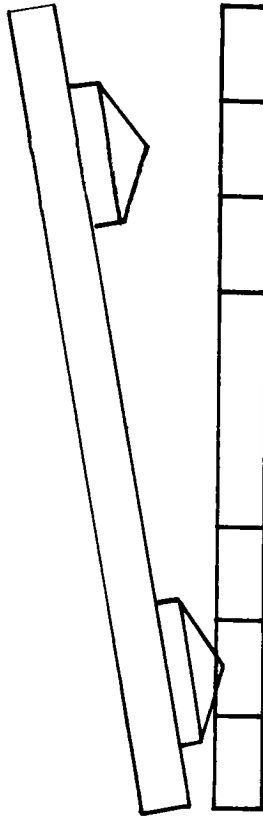


COMPLIANCE DEVICE SPRING FORCE

VARIOUS MODES OF DISPLACEMENT

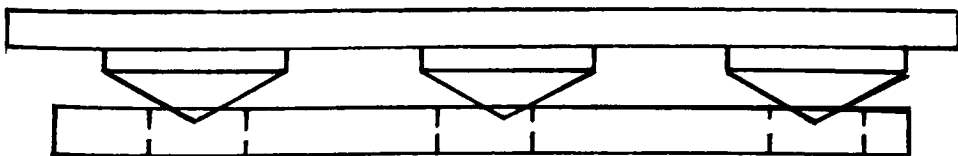


MODE I :  
SLIPPAGE



MODE II :  
LIFTING

MODE III : ROTATION



## DESCRIPTION OF DISPLACEMENTS

- (I) SLIPPAGE : CENTER PLATE MOVES PARALLEL TO THE SECURED PLATE
- (II) LIFTING : CENTERING PLATE ROTATES AROUND ONE OF ITS CONES WHILE THE OTHER TWO LIFT OFF
- (III) ROTATION : CENTERING PLATE ROTATES AROUND ITS OWN CENTER

\* NOTE: DISPLACEMENTS (I) AND (III) ARE SIMILAR, THUS ONLY DISPLACEMENTS (II) AND (III) WILL BE CONSIDERD.

\*\* NOTE: THE COMPLIANCE DEVICE HAS THREE(3) CENTERING CONES EQUALLY SPCED.

THE MAXIMUM ALLOWABLE FORCE AT THE END OF THE END-EFFECTOR NEEDS TO BE DETERMINED FROM THE MAXIMUM DYNAMIC LOADING EXERTED ONTO THE WRIST DURING NORMAL OPERATIONS.

## MODES OF OPERATIONS

- A) LOWER BASKET LOADING: CENTER OF MASS IS BELOW THE COMPLIANCE DEVICE
- B) UPPER BASKET LOADING: CENTER OF MASS IS ABOVE THE COMPLIANCE DEVICE
- C) SEPARATOR TRAY PLACEMENT:  
COMPLIANCE DEVICE IS HORIZONTAL  
WITH THE SEPARATOR TRAY BELOW  
IT

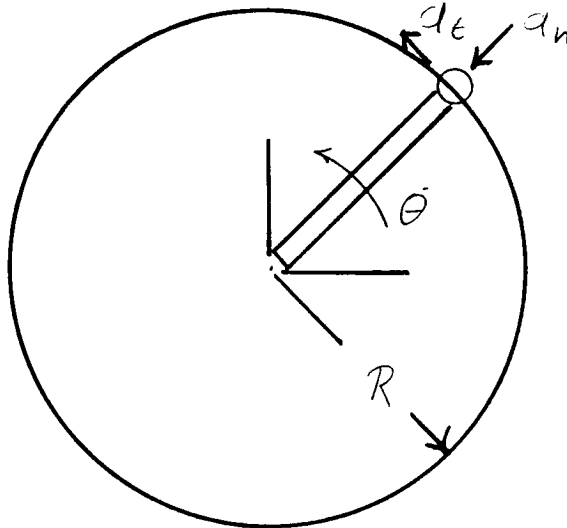
## MAXIMUM DYNAMIC LOADING SITUATION

GMF M-1A CYLINDRICAL COORDINATE ROBOT

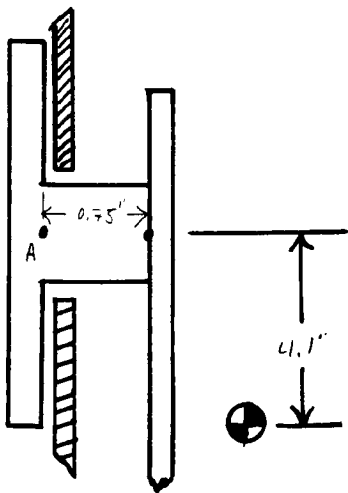
MAXIMUM ROTATIONAL SPEED:

$$R = 72.2''$$

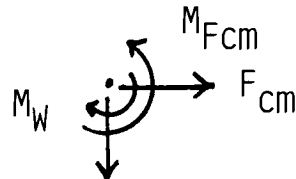
$$\dot{\theta} = 60 \text{ DEG./s.} = \pi/3 \text{ RAD/S}$$



$$\begin{aligned} A_N &= R \dot{\theta}^2 = (72.2'')(\pi/3 \text{ RAD/S})^2 \\ &= 79.2 \text{ in/s}^2 \end{aligned}$$



DYNAMIC AND STATIC FORCES ON A DUE  
TO THE END-EFFECTOR ONLY:



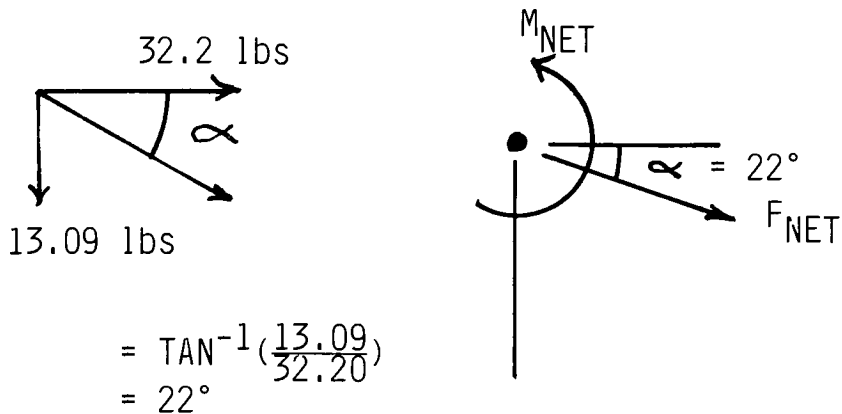
$$W = 13.09 \text{ lbs}$$

$$M_W = 27.75 \text{ lb-in}$$

$$F_{cm} = 32.2 \text{ lbs}$$

$$M_{cm} = 132 \text{ lb-in}$$

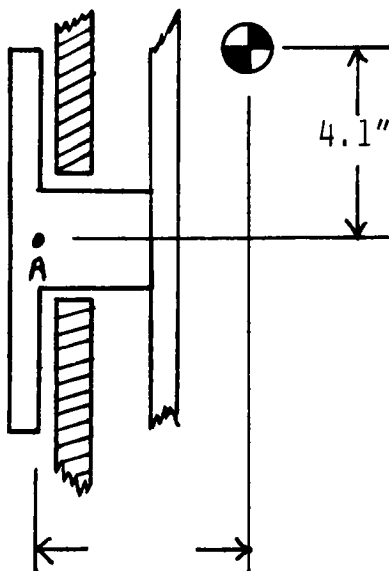
## NET DYNAMIC LOADING AT POINT A



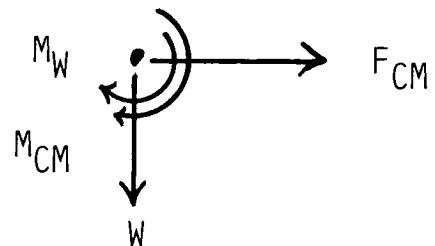
$$M_{\text{NET}} = 104.3 \text{ lb-in CCW @ POINT A}$$

$$F_{\text{NET}} = 34.8 \text{ lbs @ } -22^\circ$$

### LOADING B



### DYNAMIC AND STATIC FORCES ON A



$$W = 13.09 \text{ lbs}$$

$$M_W = 27.75 \text{ lb-in CW}$$

$$F_{\text{CM}} = 32.2 \text{ lb}$$

$$M_{\text{CM}} = 132.0 \text{ lb-in cw}$$

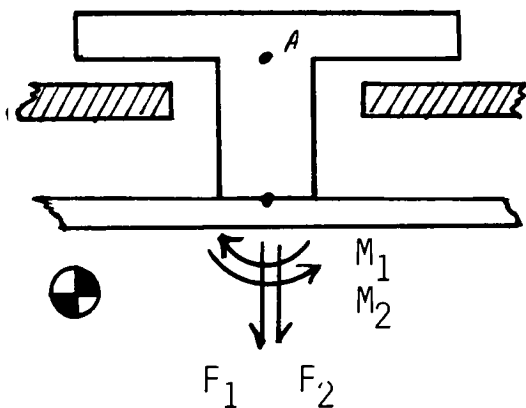
## NET DYNAMIC LOADING

$$M_{\text{NET}} = 187.5 \text{ lb-in CW}$$

LOADING B

$$F_{\text{NET}} = 34.8 \text{ lbs @ } -22^\circ$$

## LOADING C



$M_1, M_2, F_1, F_2$  ARE DUE TO THE SEPARATOR TRAY

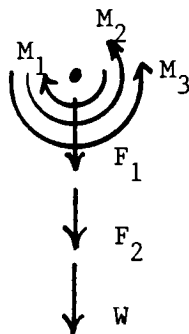
$$F_1 = F_2 = -5 \text{ lbs}$$

$$M_1 = 30 \text{ lb-in CW}$$

$$M_2 = 77.5 \text{ lb-in CCW}$$

STATIC LOADING

AT POINT A



$$M_{\text{NET}} = 75.25 \text{ lb-in}$$

$$F_{\text{NET}} = 23.09 \text{ lbs}$$

\* NOTE: WHEN HANDLING THE SEPARATOR TRAY, THE ROBOT WILL BE MOVING SLOWLY, THUS THE ADDITIONAL DYNAMIC LOADING FORCE WILL NEGLIGIBLE

THUS AT POINT A , THE MAXIMUM LOAD SITUATION IS MODE B.

$$F_{MAX} = 34.76 \text{ lb at } -22^\circ$$

$$M_{MAX} = 187.5 \text{ lb-in}$$

BEHIND EACH CENTERING CONE (SMALL CIRCLES SHOWN BELOW) THERE WILL A SPRING. ALL THAT IS LEFT IS TO CALCULATE THE REQUIRED SPRING FORCE TO KEEP THE CENTERING PLATE IN PLACE WHILE MOVING.

1st NEED TO FIND THE DISTANCE A

$$A = (1 \frac{9}{16} \text{") SIN}(30^\circ) = 0.78 \text{"}$$

$$M_{MAX} = 2(A (F_{SPRING})_{MIN})$$

$$(F_{SPRING})_{MIN} = 120 \text{ lbs}$$

